IRC:SP:140-2024

GUIDELINES FOR DESIGN OF SHORT SLAB CONCRETE PAVEMENTS FOR HIGHWAYS AND EXPRESSWAYS

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GUIDELINES FOR DESIGN OF SHORT SLAB CONCRETE PAVEMENTS FOR HIGHWAYS AND EXPRESSWAYS

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SYMBOLS AND ABBREVIATIONS

Symbols and abbreviations are defined where they occur first. Some of them are local in nature and omitted from the following since they have no bearing in other sections.

A = Initial number of commercial vehicles per day in the year when road is opened to traffic

B = Average number of axles per commercial truck

BUC = Bottom-Up Cracking

C = Cumulative Number of Commercial Vehicles during the Design Period

CBR = California Bearing Ratio, %

CFD = Cumulative Fatigue Damage

CS = Concrete Shoulder

CTB = Cement Treated Base

CTSB = Cement Treated Subbase

CVPD = Commercial Vehicles Per Day

DLC = Dry Lean Concrete

DLN = Lane Distribution Factor for Longitudinal Cracking with Negative Temperature Differential

DLP = Lane Distribution Factor for Longitudinal Cracking with Positive Temperature Differential

DTE = Deflection Transfer Efficiency, %

DTN = Lane Distribution Factor for Transverse Cracking with Negative Temperature Differential

DTP = Lane Distribution Factor for Transverse Cracking with Positive Temperature Differential

E = Modulus of Elasticity of Concrete, MPa

F_b = Allowable Bearing Stress, MPa

F_{bmax} = Maximum Bearing Stress, MPa

f_{ck} = Characteristic Compressive Cube Strength of Concrete, MPa

f_{cr} = Characteristic Flexural Strength at 28 days, MPa

f'_{cr} = Target Mean Flexural Strength at 28 days, MPa

FEM = Finite Element Method

GSB = Granular Sub-Base

h = Thickness of Slab, m

k = Effective Modulus of Subgrade Reaction, MPa/m

k_{Φ} = Modulus of Subgrade Reaction (MPa/m) with Plate Diameter Φ

k_{750} = Modulus of Subgrade Reaction (MPa/m) with Plate Diameter 750 mm

l = Radius of Relative Stiffness, m

LTE = Load Transfer Efficiency, %

MEPDG= Mechanistic Empirical Pavement Design Guide

N = Fatigue Life

n = Design Period, years

NCHRP= National Cooperative Highway Research Program

n_i = Number of Expected Repetitions for the i^{th} Load Group

N_i = Number of Allowable Repetitions (Fatigue Life) for the i^{th} Load Group

N_r = Fatigue Life at Load Level 'r'

OMC = Optimum Moisture Content

P = Single/Tandem/Tridem Axle Load, kN

pci = Pound per Cubic Inch

PQC = Pavement Quality Concrete

P_t = Load transferred by Dowel Bar, kN

R = Flexural Stiffness, MN.m

r = Annual Rate of Growth of Commercial Traffic Volume (expressed as decimal)

S_{st} = Allowable Working Stress of Steel, MPa

S = Flexural Stress in Slab, MPa

SR = Stress Ratio

SR_r = Stress Ratio at Load Level 'r'

TD = Temperature Differential

TDC = Top-down Cracking

U_C = Uniformity Coefficient

W = Weight of Slab, kN/m^2

Z = Joint Width, mm

Za = A factor corresponding to desired confidence level, which is 1.96 for 5% confidence level

α = Coefficient of Thermal Expansion, /^oC

β = Relative Stiffness of Dowel Bar Embedded in Concrete, MPa/m

γ = Unit Weight of Concrete, kN/cum

φ = Plate Diameter, m

μ = Poisson's Ratio of Concrete

σ = Standard Deviation of Field Test Samples, MPa

ΔN = Negative Temperature Differential

ΔP = Positive Temperature Differential

ΔT = Temperature Differential, ^0C (also designated as TD)

*** All the Figures/Drawings presented in this document are representative only and are not to scale.**

GUIDELINES FOR DESIGN OF SHORT SLAB CONCRETE PAVEMENTS FOR HIGHWAYS AND EXPRESSWAYS

1. INTRODUCTION

The Rigid Pavement Committee (H-3) of Indian Roads Congress (IRC) took up the task of preparation of draft Guidelines for Design of Short Slab Concrete Pavements for Highways and Expressways and a subgroup was constituted comprising Prof. (Dr.) M. Amaranatha Reddy, (Subgroup Chairman), Prof. (Dr.) K. Sudhakar Reddy, Shri B.V. Joga Rao, Prof. (Dr.) A. Veeraragavan, Dr. V. Ramachandra, Shri P.L. Bongirwar, Shri Satander Kumar and Shri Ashutosh Gautam.

The initial draft on "Guidelines for Design of Short Slab Concrete Pavements (SSCP) for Highways and Expressways" was prepared by subgroup chairman and the other two members of IIT Kharagpur and was discussed with the other members of the sub-committee and was submitted to the H-3 Committee of the Indian Roads Congress for consideration. The guidelines are based on the research work carried by Transportation Engineering Section of IIT Kharagpur on "Laboratory and Field Investigation of Paneled Cement Concrete Pavements for Highways" initiated by Late Prof. B.B. Pandey and sponsored by NHAI, New Delhi.

The draft document was deliberated in various meetings of H-3 Committee and was finalized in the meeting held on 01.06.2023 and was recommended for placing to the Highways Specifications and Standards (HSS) Committee.

The document was discussed by the Highways Specifications and Standards Committee (HSS) during its meeting held on 27.06.2023. The HSS Committee approved this draft subject to incorporation of written and verbal comments received and submitting the revised draft to the Executive Committee (EC) and Council. The EC in its meeting held on 06.07.2023, approved the draft for placing before the Council. The 225th Mid-Term Council, in its meeting held on 7th July, 2023 at Raipur (Chhattisgarh) considered and approved draft "Guidelines for Design of Short Slab Concrete Pavements for Highways and Expressways" for printing.

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2. GENERAL

Short Slab Concrete Pavement (SSCP) is a concrete pavement constructed with a shorter joint groove spacing of 1.0 m to 2.0 m. **Figs. 1(a) and (b)** show the views of two short slab concrete pavements constructed by placing the concrete layer over (a) Dry-Lean Concrete (DLC) and (b) existing bituminous layer respectively. The shorter joint groove spacing results in interconnected slabs (typically square slabs) of edge length 1.0 to 2.0 m as most of the joint grooves develop into active joints (full-depth cracks). The thickness requirement of SSCP is generally less than that of a conventional concrete pavement due to the lower bending moment caused due to the shorter span. As the slab/panel/block size is reduced from the 3.5 m x 4.5 m size, which is the typical slab size adopted for the high traffic volume roads in India (IRC:58 guidelines), to a smaller size, the mechanism of load transfer through the concrete layer shifts from a predominantly flexure mode to a more direct compression mode as smaller slabs undergo less flexure. Thus, it is possible to have concrete layers of smaller thicknesses when the slab size is reduced. The day-time as well as the night time temperature differentials come down with the reduced thickness of slab and as a result, the curling stresses will also be less.

Fig. 1(a) Two Views of SSCP Test Section over DLC Base on NH-18 near Ghatshila, Jharkhand

Fig. 1 (b) Two Views of SSCP Test Section over existing Bituminous Base on NH-18 near Baharagora, Jharkhand

Short slabs or panels are formed by introducing primary saw-cut of 3.0 to 5.0 mm width to a depth of 1/4th to 1/3rd the thickness of the slab within 8 to 16 hours of placement of concrete (Raoufi et al., 2008; Zollinger et al., 1994). The purpose of the saw-cut is to reduce drying shrinkage stresses and to produce controlled full-depth cracks during the initial period and during the service life period of the pavement. The aggregate interlocking created by the formation of full-depth crack below the groove-cut facilitates load transfer among adjacent slabs in SSCP. Unlike the conventional Jointed Plain Concrete Pavement (JPCP), SSCP does not require dowel bars or tie bars, except at construction joints, making it an economical option (Pradena and Houben, 2015).

Considering the advantage of the reduction in slab thickness which can be gained by the reduction in the size of the slab, it is necessary that suitable guidelines are made available for the design of short slab concrete pavements. Different issues related to the design and construction of short slab concrete pavements in India are currently covered by IRC:SP:76 guidelines for the case of thin white topping, which is a thin slab with short joint spacing placed as an overlay over an existing bituminous pavement. Typical short slab sizes considered in IRC:SP:76 guidelines are in the range of 1.0 m × 1.0 m to 1.5 m × 1.5 m and the failure mode considered is corner cracking

under negative temperature differential condition in the slab. The composite action of the slab and the foundation bituminous layer is expected to result in the reduction of tensile stresses in the concrete slab. For the calculation of corner tensile stress (considered to be critical for short slabs), two separate equations (one for 8 T single axle load and another for 16 T tandem axle load) were adopted. In these equations, the magnitude of the corner tensile stress depends on the modulus of subgrade reaction (k) of the foundation, radius of relative stiffness *(l)* of the pavement and the edge length of the square slab. For other axle loads, the stresses have to be linearly extrapolated. The Cumulative Fatigue Damage (CFD) approach recommended in IRC:58 guidelines is to be followed for structural design of the pavement using the stresses calculated by these equations. The procedure for the estimation of the effective modulus of subgrade reaction on top of the bituminous layer of the in-service bituminous pavement, which serves as the foundation for the short slab concrete pavement, is given in IRC:SP:76 guidelines.

The present guidelines provide the structural design methodology for short slab concrete pavements for (a) different slab sizes (b) different types of foundation and different values of foundation strength (modulus of subgrade reaction) (c) different critical loading conditions for longitudinal and/or transverse bottom-up and /or top-down cracking and (d) single, tandem and tridem axle loads of varying magnitudes. The Cumulative Fatigue Damage (CFD) approach adopted in IRC:58 guidelines has been used in these guidelines also for checking the adequacy of the SSC pavement for bottom-up and top-down longitudinal and transverse cracking resistance.

3. BACKGROUND

The current guidelines are prepared based on extensive laboratory, field and analytical work carried out during 2016-2022 by IIT Kharagpur as a part of the research project on "Laboratory and Field Investigation of Short Slab Cement Concrete Pavements for Highways", sponsored by NHAI, New Delhi (NHAI Final Report, 2022). Two test sections, each of 1.5 km length, were constructed for this purpose on NH-18 in on-going projects. The test sections were constructed on NH-18 in the state of Jharkhand with slab sizes of 1.0 m × 1.0 m, 1.5 m × 1.5 m and 2.0 m × 2.0 m and with thicknesses of 180, 200 and 220 mm respectively. These combinations of short slab concrete pavement layer were constructed over existing bituminous pavement and also over a newly constructed Dry Lean Concrete (DLC) subbase. The structural response of the test sections was evaluated once every six months over a period of 5 years using the Falling Weight Deflectometer (FWD) developed by IIT Kharagpur to gather information about the structural performance of the slabs and joints and its variation with time. Finite Element (FE) models were developed for analysis of multi-slab systems of SSCP. For ease of analysis and design, using the results of FE analysis carried out for a large number of pavement section combinations subjected to various combinations of loads and temperature differentials, regression equations were developed for estimation of critical tensile stress in the concrete layer (NHAI Final report, 2022).

The salient features of the FE models developed for analysis of SSC pavements and the regression models developed for the estimation of critical tensile stresses in SSCP are presented in these guidelines along with the approach to be followed for design of different types of SSC pavements.

4. SCOPE OF THE GUIDELINES

These guidelines cover the design of Short Slab Concrete Pavements (SSCP) with and without concrete shoulders for different short slab sizes: 1.0 m × 1.0 m, 1.25 m × 1.25 m, 1.5 m × 1.5 m, 1.75 m × 1.75 m and 2.0 m × 2.0 m. The present guidelines are applicable for unbonded short slab concrete pavements. Regression equations are presented in these guidelines for analysis of different slab sizes separately since the critical load positions and the corresponding magnitudes of critical stresses vary depending on the size of the short slab. The current guidelines are applicable to pavements having more than 450 Commercial Vehicles Per Day (CVPD) (two-way traffic). For analysis of different types of SSC pavements, the pavement system is considered as a slab over Winkler foundation. The modulus of subgrade reaction parameter of the multi-layer foundation (subgrade, subbase and base) representing Winkler foundation is selected using appropriate guidelines given in IRC:58 and IRC:SP:76. The requirements and specifications for different layer materials are detailed in later sections of the guidelines. The following SSC pavement types are considered.

(a) New construction with Dry Lean Concrete (DLC) base and granular or Cement-Treated Sub-Base (CTSB) placed over subgrade as the foundation for the short slab concrete layer and with a polythene sheet or non-woven geotextile separation layer between the PQC slab and DLC layer (as illustrated in **Fig. 2**).

(b) New construction with Cement-Treated Base (CTB) and Cement Treated Sub Base (CTSB) placed over subgrade as the foundation for the short slab concrete layer and with a polythene sheet or non-woven geotextile separation layer between the slab and CTB layer (as illustrated in **Fig. 3**).

(c) New construction with Cement-Treated Base (CTB) and Cement-Treated Sub-Base (CTSB) placed over subgrade as the foundation for the short slab concrete layer with a thin bituminous concrete layer of 30 to 40 mm thickness with BC-2 aggregate gradation (MoRTH, 2013) with VG40 bitumen only as the debonding layer (as illustrated in **Fig. 4**).

(d) New or existing pavement with a minimum bituminous layer thickness of 75 mm (after surface milling in the case of in-service pavement) over an unbound or cement treated aggregate base and an unbound or cement treated granular subbase layer, placed over the subgrade as the foundation for the short slab concrete pavement layer (as illustrated in **Fig. 5**). Bituminous layer provides a non-erodible and strain accommodative support for the short slab pavement quality concrete layer. No separation layer required between slab and bituminous layer.

A Minimum soaked CBR value of 5.0 % is recommended for subgrade in new construction

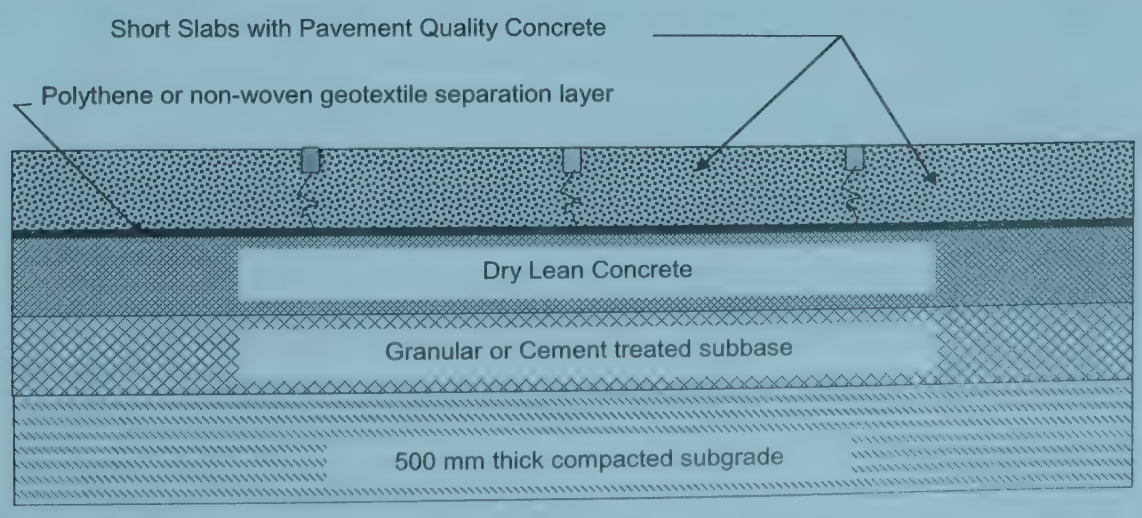

Short Slabs with Pavement Quality Concrete
Polythene or non-woven geotextile separation layer
Dry Lean Concrete
Granular or Cement treated subbase
500 mm thick compacted subgrade

Fig. 2 SSCP with DLC Base (Unbonded) and Granular/Cement Treated Subbase (CTSB)

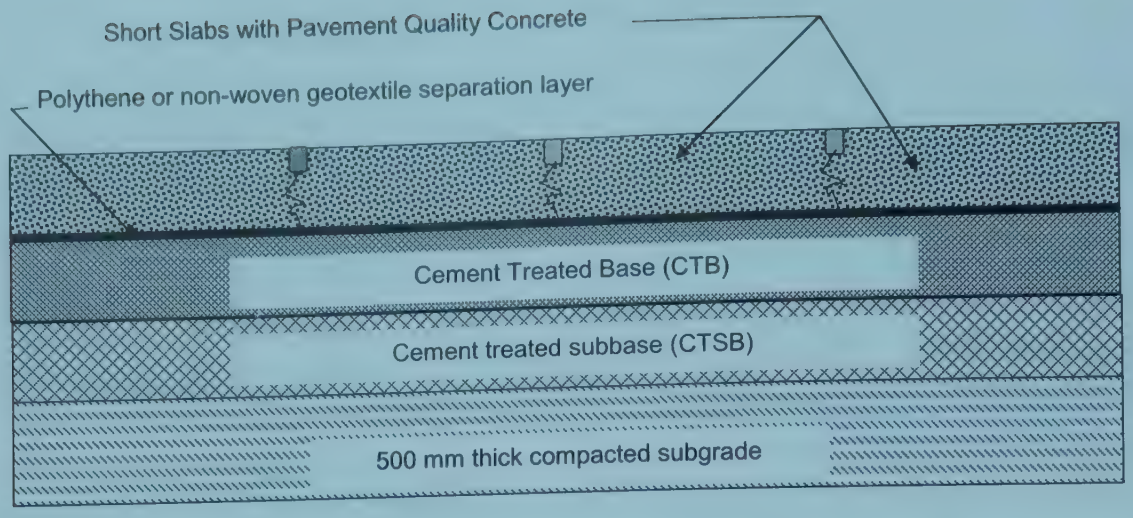

Short Slabs with Pavement Quality Concrete
Polythene or non-woven geotextile separation layer
Cement Treated Base (CTB)
Cement treated subbase (CTSB)
500 mm thick compacted subgrade

Fig. 3 SSCP with CTB (Unbonded) and Cement Treated Subbase (CTSB) Debonded with Polythene Sheet or Non-Woven Geo Textile

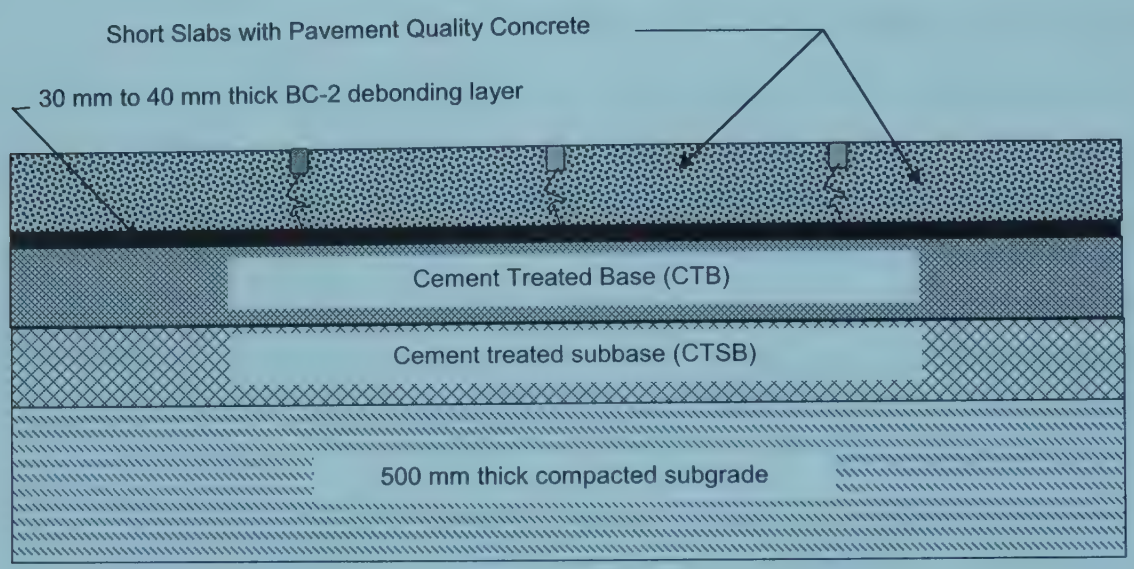

Short Slabs with Pavement Quality Concrete
30 mm to 40 mm thick BC-2 debonding layer
Cement Treated Base (CTB)
Cement treated subbase (CTSB)
500 mm thick compacted subgrade

Fig. 4 SSCP with CTB (Unbonded) and Cement Treated Subbase (CTSB) with Thin BC-2 Mix as Debonding Layer

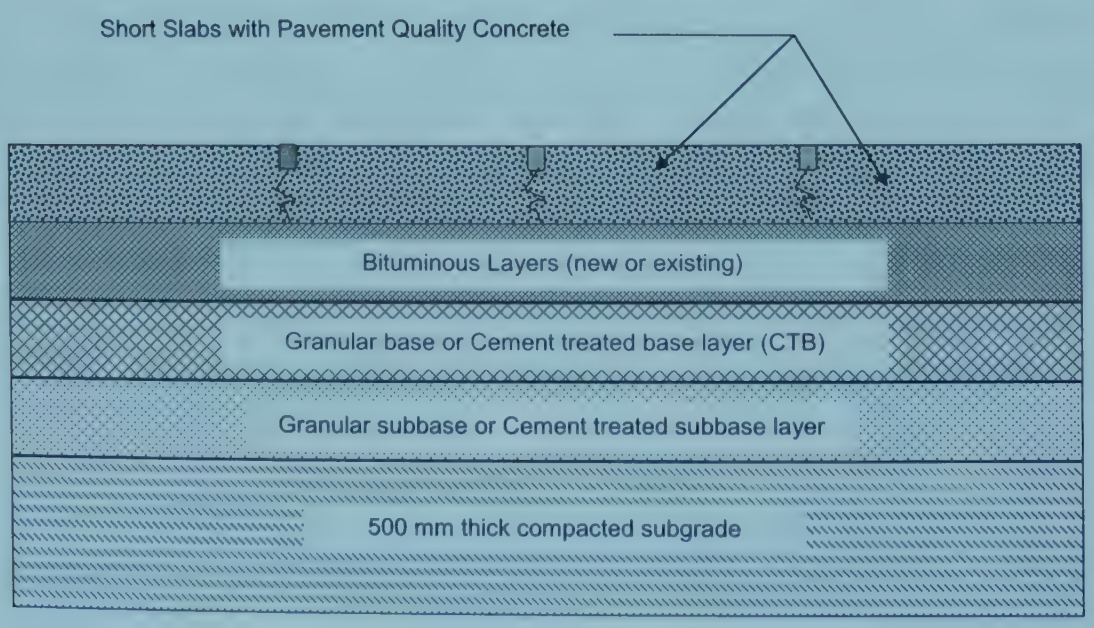

Short Slabs with Pavement Quality Concrete
Bituminous Layers (new or existing)
Granular base or Cement treated base layer (CTB)
Granular subbase or Cement treated subbase layer
500 mm thick compacted subgrade

Fig. 5 SSCP over New or Existing Bituminous Pavement

These guidelines may need revision from time to time in the light of additional experience to be gathered in future on the structural and functional performance of short slab concrete pavements built on different categories of highways. It is recommended that all the organizations that are concerned with design, construction and maintenance of SSCP should keep a detailed record of

construction, maintenance and rehabilitation, commercial traffic volumes and load characteristics and structural and functional performance evaluation data so that these can be used for future revision of the guidelines.

5. SALIENT FEATURES OF THE PRESENT GUIDELINES

The salient features of these guidelines, prepared for the analysis and design of Short Slab Concrete Pavements (SSCP), are listed below.

(i) Analysis and design methodologies are presented for SSCPs with different square slabs of sizes; 1.0 m, 1.25 m, 1.5 m, 1.75 m and 2.0 m.

(ii) A simplified design approach is suggested for (a) rectangular slabs with aspect ratio (length/breadth) of less than 1.2 and (b) square slabs of intermediate (different from the five sizes mentioned in (i)).

(iii) SSC Pavements with and without concrete shoulders are considered

(iv) Various critical combinations of axle loads and temperature differentials (day-time positive and night-time negative) are considered for analyzing the longitudinal and transverse cracking, that may initiate either from the top (Top-Down Cracking - TDC) or from the bottom (Bottom-Up Cracking - BUC) of the slab.

(v) The principle of Cumulative Fatigue Damages (CFD), as adopted in IRC:58 guidelines, is considered for damage assessment of the SSCPs and for their structural design.

(vi) Consideration was given to built-in permanent curl in the analysis of flexural stresses as done in the IRC:58 guidelines.

(vii) A terminal Deflection Transfer Efficiency (DTE) of the SSCP joints, which can be measured using a Falling Weight Deflectometer (FWD), of 50 percent was considered in the analysis.

(viii) Multi-slab (nine-slab system) Finite Element (FE) models were developed for various combinations of short slab sizes and thicknesses, and foundation layer stiffnesses and for different combinations of axle types (single, tandem and tridem) applied in different critical positions and for different combinations of axle loads with positive and negative temperature differentials in the slab. A total of more than 50,000 scripts were generated for the FE analysis (with various parameters) to analyze the slab system at a DTE of 50 percent.

(ix) A sample set of stress charts (similar to the stress charts of IRC:58 guidelines) are also presented in the guidelines for reference.

(x) A detailed design example is provided considering different slab sizes and concrete shoulder cases by taking the design example statement given in IRC:58 guidelines.

6. FACTORS GOVERNING THE STRUCTURAL DESIGN OF SSCP

The main factors governing the design of SSCP are design period, design commercial traffic volume, composition of commercial traffic in terms of single, tandem, tridem and multi-axles, axle load spectrum, tyre pressure, lateral placement characteristics, directional distribution of traffic, foundation layers and the effective strength of foundation and vertical temperature differential (positive and negative) in the slab. These design inputs can be used to analyze and design the thicknesses of SSC pavement (with and without concrete shoulders) with selected slab size. The following sections of the guidelines discuss various issues related to the selection of design traffic, temperature differential, materials to be used in different layers and the selection of relevant material characteristics for analysis and design.

6.1 Axle Load Characteristics

Axle load spectrum of the commercial vehicles is required to estimate the design repetitions of single, tandem and tridem axles of different load category expected during the design period. The minimum percentages of commercial vehicles to be weighed during the axle load survey should be 10 percent for two-way Commercial Vehicles Per Day (CVPD) exceeding 6000, 15 percent for CVPD in the range of 3000 to 6000 and 20 percent for CVPD less than 3000. Axle load survey may be conducted for a continuous 48-hour period in both directions. The vehicles to be surveyed may be selected randomly to avoid bias. If the spacing of consecutive axles (wheel base) is more than 2.4 m, each axle shall be considered as a single axle. The intervals at which the axle load groups should be classified for fatigue damage analysis are:

Single axle 10 kN

Tandem axle 20 kN

Tridem axle 30 kN

For most of the commercial highway vehicles, the commonly used tyre inflation pressures range from about 0.7 MPa to 1.0 MPa. A tyre pressure of 0.8 MPa is considered appropriate for analysis and design of SSCP in these guidelines which is similar to the recommendation made in IRC:58 guidelines.

6.2 Design Period

SSCP may be designed for a service life of up to 30 years. However, the design engineer should use his/her judgment about the design period taking into consideration different factors such as traffic volume, uncertainty of traffic growth rate, the capacity of the road and the possibility of augmentation of capacity by widening of carriageway etc.

6.3 Design Traffic

The estimation of the number of single, tandem and tridem axles of different load groups expected to be applied at critical load positions over the slab and which are relevant for bottom-up and top-down cracking cases in longitudinal as well as transverse cracking failures, is one of the most critical steps in the design of SSCP. The estimation of the total number of commercial vehicles

expected during the design period, should normally be based on seven-day 24-hour count made in accordance with IRC:9 "Traffic Census on Non-Urban Roads". The actual value of the annual rate of growth 'r' of commercial vehicles should be determined using appropriate methods. As per IRC:SP:84, the annual growth rate of commercial vehicles shall be taken to be a minimum of 5 % (as adopted in IRC:58 guidelines). The traffic counts and the corresponding traffic estimates should indicate the day and night traffic trends as the traffic during the day hours is generally responsible for Bottom-Up Cracking (BUC) whereas the night time traffic may cause Top-Down Cracking (TDC).

The expected number of applications of different axle load groups during the design period can be estimated using the details of commercial traffic volume, expected rate of growth of commercial traffic, information about axle load spectrum and the number of single, tandem and tridem axles obtained from axle load survey. Front axles (steering axle) with single wheels on both side cause relatively negligible bottom-up and top-down fatigue damage and hence can be neglected in the analysis. The cumulative number of commercial vehicles expected during the design period may be estimated from the following expression.

$$C = \frac{365 \times A \times [(1+r)^n - 1]}{r} \qquad \text{(Eq.1)}$$

Where,

C = Cumulative number of commercial vehicles during the design period

A = Initial number of commercial vehicles per day in the year when the road is opened to traffic

r = Annual rate of growth of commercial traffic volume (expressed as decimal)

n = Design period in years

The edge flexural stress caused by axle loads for Bottom-Up Cracking (BUC) is maximum when the tyre imprint of the outer wheel touches the longitudinal edge. When the tyre position is away even by 150 mm from the longitudinal edge, stress in the edge region is reduced substantially. The magnitude of edge flexural stress is small when the wheels are close to the transverse joints during day time. Typical lateral distribution characteristics of wheel paths of commercial vehicles observed on Indian highways indicate that very few wheels of vehicles are tangential to the longitudinal edge or longitudinal joint on two-lane two-way roads and divided multi-lane highways.

Taking into consideration these issues, it is recommended that 25 per cent of the total two-way commercial traffic may be considered as design traffic for two-lane two-way roads for the analysis of fatigue damage. In the case of four-lane and other multi-lane divided highways, 25 per cent of the total commercial traffic in the direction of predominant traffic may be considered for design of pavement, which is similar to the recommendation made in IRC:58 guidelines.

6.4 Temperature Differential

The temperature differential between the top and bottom surfaces of concrete pavement causes the concrete slab to curl, giving rise to curling (thermal flexural) stresses. The temperature differential is a function of solar radiation received by the pavement surface, wind velocity, thermal diffusivity of concrete, latitude, longitude and elevation of the place and is thus affected by geographical features of the pavement location as discussed in IRC:58 guidelines. The typical values of temperature differentials for different regions in India may be adopted from Table 1 of IRC:58 guidelines. The recommendation given in the IRC:58 guidelines, for the selection of zero-stress temperature differential value, is adopted in these guidelines. While it is ideal to carry out hourly cumulative fatigue damage analysis, the data required for such a detailed analysis is generally not available. Hence, as recommended in IRC:58 guidelines, it is suggested that the maximum positive and negative temperature differentials respectively, may be assumed to be constant for the six-hour period during the day between 10 AM and 4 PM hours and for the six-hour period between 12 Mid-night and 6 AM during night hours. The slab may be assumed to be free of curling stresses for the remaining 12 hours for the purpose of fatigue damage analysis as the fatigue damage caused by the combined action of load and temperature differential is considered to be insignificant during this period. The timings refer to Indian Standard Time and may be different for different geographical locations in India.

6.5 Concrete Strength

6.5.1 *Flexural Strength*

The flexural strength of concrete is required for the purpose of analysis and design of concrete slab. The grade of concrete considered in the analysis is M40. So, the concrete with the 28-day characteristic flexural strength of not less than 4.5 MPa should be used in the construction. The strength can be obtained by testing concrete beams as per the procedure given in IS: 516. Alternatively, it can be estimated from the characteristic compressive strength of concrete as per IS 456 using the following relationship:

$$f_{cr} = 0.7 \times \sqrt{f_{ck}} \qquad \text{(Eq. 2)}$$

Where,

f_{cr} = Characteristic flexural strength (modulus of rupture), MPa

f_{ck} = Characteristic compressive cube strength of concrete, MPa

Concrete mix design is usually done based on 28-day strength. For thickness design of concrete pavements, use of 90-day strength can be permitted in view of the fact that (i) the concrete pavement is opened to traffic long after the construction (ii) the number of repetitions of load and hence the cumulative fatigue damage of concrete, are very small during the initial period of 90 days even if the pavement is opened to traffic after 28-day and (iii) the stress analysis is done for a terminal condition of the pavement slab when load transfer efficiency of transverse joints and concrete shoulder joints (longitudinal joints) is low. The 90-day flexural strength may be obtained by multiplying the 28-day flexural strength by a factor of 1.10. In no case should the 28-day characteristic flexural strength of the Pavement Quality Concrete (PQC) be less than 4.5 MPa before opening the road to regular traffic.

The target mean flexural strength to be achieved while designing the mix should be such that there is 95 percent probability that the characteristic strength would be achieved when the mix

is produced in the field (confidence level = 95%). The target mean flexural strength may be estimated by the following equation

$$f'_{cr} = f_{cr} + Z_a\sigma \qquad \text{(Eq. 3)}$$

Where,

f'_{cr} = Target mean flexural strength at 28 days, MPa

f_{cr} = Characteristic flexural strength at 28 days, MPa

Z_a = A factor corresponding to the desired confidence level, which is 1.96 for 95% confidence level

σ = Standard deviation of the flexural strength of field test samples, MPa

6.5.2 *Modulus of Elasticity and Poisson's Ratio of Concrete*

The modulus of elasticity (E) and Poisson's ratio (μ) of cement concrete vary with concrete materials and strength. The elastic modulus increases with increase in strength, and Poisson's ratio decreases with increase in the modulus of elasticity. While it is desirable that the values of these parameters are ascertained experimentally for the concrete mix and the materials to be used in the construction, this information may not always be available at the design stage. A 25 % variation in E and μ values will have only a marginal effect on the flexural stresses in the pavement concrete. The following values are adopted in these guidelines for stress analysis for concrete with 28-day flexural strength of 4.5 MPa (4.95 MPa for 90-day strength).

Modulus of elasticity of concrete, E = 30,000 MPa

Poisson's ratio, μ = 0.15

6.5.3 *Coefficient of Thermal Expansion*

The coefficient of thermal expansion of concrete *(α)* is dependent to a great extent on the type of aggregates used in concrete as the aggregate constitutes the major portion in the concrete mix. However, for design purpose, a value of $\alpha = 10 \times 10^{-6}/^{\circ}C$ is adopted.

6.5.4 *Fatigue Behavior of Cement Concrete*

Due to repeated application of flexural stresses by the traffic loads, progressive fatigue damage takes place in the cement concrete slab in the form of gradual development of micro-cracks especially when the ratio between the applied flexural stress and the flexural strength of concrete is high. This ratio is termed as Stress Ratio (SR). If the SR is less than 0.45, the concrete is expected to sustain infinite number of repetitions. As the stress ratio increases, the number of load repetitions required to cause cracking decreases. The relation between Fatigue Life (N) and stress ratio is given as:

N = *unlimited for* $SR < 0.45$ (Eq. 4)

$$N = \left[\frac{4.2577}{SR - 0.4325}\right]^{3.268} \quad \textit{for } 0.45 \le SR \le 0.55 \qquad \text{(Eq. 5)}$$

$$\log_{10} N = \frac{0.9718 - SR}{0.0828} \quad \textit{for } SR > 0.55 \qquad \text{(Eq. 6)}$$

These fatigue criteria are used in these guidelines for checking the adequacy of the pavement slab on the basis of Miner's hypothesis. It is assumed that the fatigue resistance not consumed by repetitions of one load is available for repetitions of other loads. The above fatigue criteria developed by Portland Cement Association (PCA, 1984) are conservative and can be used for the analysis of bottom-up and top-down cracking.

6.6 Foundation Layers

As can be seen in **Figs. 2 to 5,** the foundation for the SSCP layer may consist of different combinations of materials including subgrade soils, granular material, cemented bases and subbases and bituminous layers. The following sections present the requirement of the foundation layers and the materials used in these layers.

6.6.1 *Dry Lean Concrete Sub-base*

The strength requirements of Dry Lean Concrete (DLC) layer are similar to those mentioned in IRC:58 guidelines. 7-day compressive strength of minimum 7 MPa and 28-day compressive strength of minimum 10 MPa, determined as per IRC:SP:49 guidelines, are recommended. The thickness of the DLC layer should be 150 mm or more.

6.6.2 *Bituminous Base*

For new or in-service pavements in which the SSCP layer is laid over existing bituminous pavement or a new bituminous pavement (white topping), the minimum thickness of the bituminous layer should be 75 mm. The bituminous layer should be in good condition, as specified in IRC:SP:76 guidelines. The Resilient Modulus (M_r) value of the bituminous mix immediately below the SSCP layer, measured as per ASTM D4123 (1995) at 35°C test temperature, should not be less than 2500 MPa for new construction and not less than 1000 MPa for in-service bituminous layers (tested using field core samples). Pre-overlay repairs for the in-service payment may be carried out as per the guidelines given in Table 1 of IRC:SP:76 guidelines before placing SSCP layer. No polythene sheet or other form of debonding layer will be required for the white topping pavement.

If it is proposed to widen the existing carriageway, existing bituminous pavement shall be widened as per relevant IRC guidelines available for widening before SSCP layer is constructed for full carriageway width.

6.6.3 *Cement Treated Base*

The requirements of the Cement Treated Base (CTB) layer shall be as per clause 8.2 of IRC:37 guidelines.

6.6.4 *Granular Sub-base*

The granular layer, when provided below the DLC layer, shall be as per the recommendations given in clause 5.7.3.9 of IRC:58 guidelines.

6.6.5 *Cement Treated Subbase*

Cement treated subbase layer shall be as per the recommendations given in clause 5.7.4 of IRC:58 guidelines.

6.6.6 *Embankment of Soil and Characteristics of Subgrade*

The materials to be used and other requirements for embankment soil shall be as per clause 5.7 of IRC:58 guidelines.

6.7 Selection of "k" Value

In the finite element analysis models developed for analysis of SSCP, the foundation has been considered as Winkler foundation which is modeled by modulus of subgrade reaction (k). The modulus of subgrade reaction value for different combinations of foundation layers may be selected either from the IRC:58 guidelines or from the IRC:SP:76 (for existing or new bituminous base case) guidelines.

6.8 Bond between SSCP and Foundation

The interface between SSCP layer and the foundation may be made smooth to reduce the interlayer friction. A debonding interlayer of a polythene sheet (white or transparent) having a minimum thickness of 125 micron or a non-woven geotextile separation layer or a 30 to 40 mm thick layer of BC2 mix as per MoRTH (2013) may be used as adopted in IRC:58 guidelines. There is no need to provide any separation sheet in the case of SSCP on new or existing bituminous pavement.

7. DESIGN OF SLAB THICKNESS

The following sections present the discussion about the expected modes of failure of SSC pavements of different size and the critical combinations of load and temperature differential contributing to these failures.

7.1 Possible Modes of Failure in Short Slab Concrete Pavement (SSCP)

In Short Slab Concrete Pavements (SSCP), the transfer of load, applied on one slab, to the adjacent slabs takes place across all the four aggregate interlocked joints. Unlike the conventional large slab jointed pavements (considered in IRC:58), where one edge is longer and hence is more prone to cracking than the other shorter edge, the square slabs of SSCP may crack in transverse as well as longitudinal directions depending on the location of the predominant wheel path and the proportion of traffic plying close to the critical load position. Available literature (Salsilli et al., 2013; Salsilli et al., 2015; Bhattacharya et al., 2019) indicates that longitudinal, transverse, and corner cracks are the predominant with the frequency of longitudinal cracks being the highest followed by transverse and corner cracks. In one of the field investigations conducted on the performance of short slab concrete pavements, it was observed that short square slabs (0.6 to 1.2 m of side) were more prone to corner cracking; medium-sized square slabs (1.5 to 2.4 m of side) experienced predominantly longitudinal cracking, and large square slabs (3.0 to 3.6 m of side) witnessed transverse cracking as the major mode of failure (Bhattacharya et al., 2019). Literature (Vandenbossche and Fagerness, 2002; NCHRP, 2004; Hossain and Sultana, 2010; Roesler et al., 2012; Li and Vandenbossche, 2013) also demonstrated that corner cracks were mostly reported for ultra-thin slabs with 3 to 4 feet (0.914 to 1.219 m) length.

7.2 Critical Stress Condition/Critical Load Position

Short slab concrete pavements are subjected to stresses due to a variety of factors acting simultaneously. The severest combination of different factors that causes the maximum damage in the pavement is the critical combination and should be considered for design. The flexural stress due to the simultaneous application of traffic loads and temperature differential is considered for design of pavement thickness. The flexural stress at the bottom of the concrete slab is the maximum during the day hours when the axle loads act midway on the pavement slab while there is a positive temperature. The condition is illustrated in **Fig. 6**. This condition is likely to produce Bottom-Up Cracking (BUC).

The positions of single, tandem and tridem axles for maximum edge flexural stress at the bottom of the pavement slab with and without concrete shoulder, are shown in **Figs. 7 and 8** respectively. The tyre imprints are considered tangential to the longitudinal edge for the transverse cracking case and tangential to the transverse edge for the longitudinal cracking case. Single axles cause the highest stress followed by tandem and tridem axles respectively. The spacing between individual axles for tandem and tridem axles varies from 1.30 m to about 1.40 m. A spacing of 1.30 m has been used in these guidelines for stress computation as done in IRC:58 design guidelines.

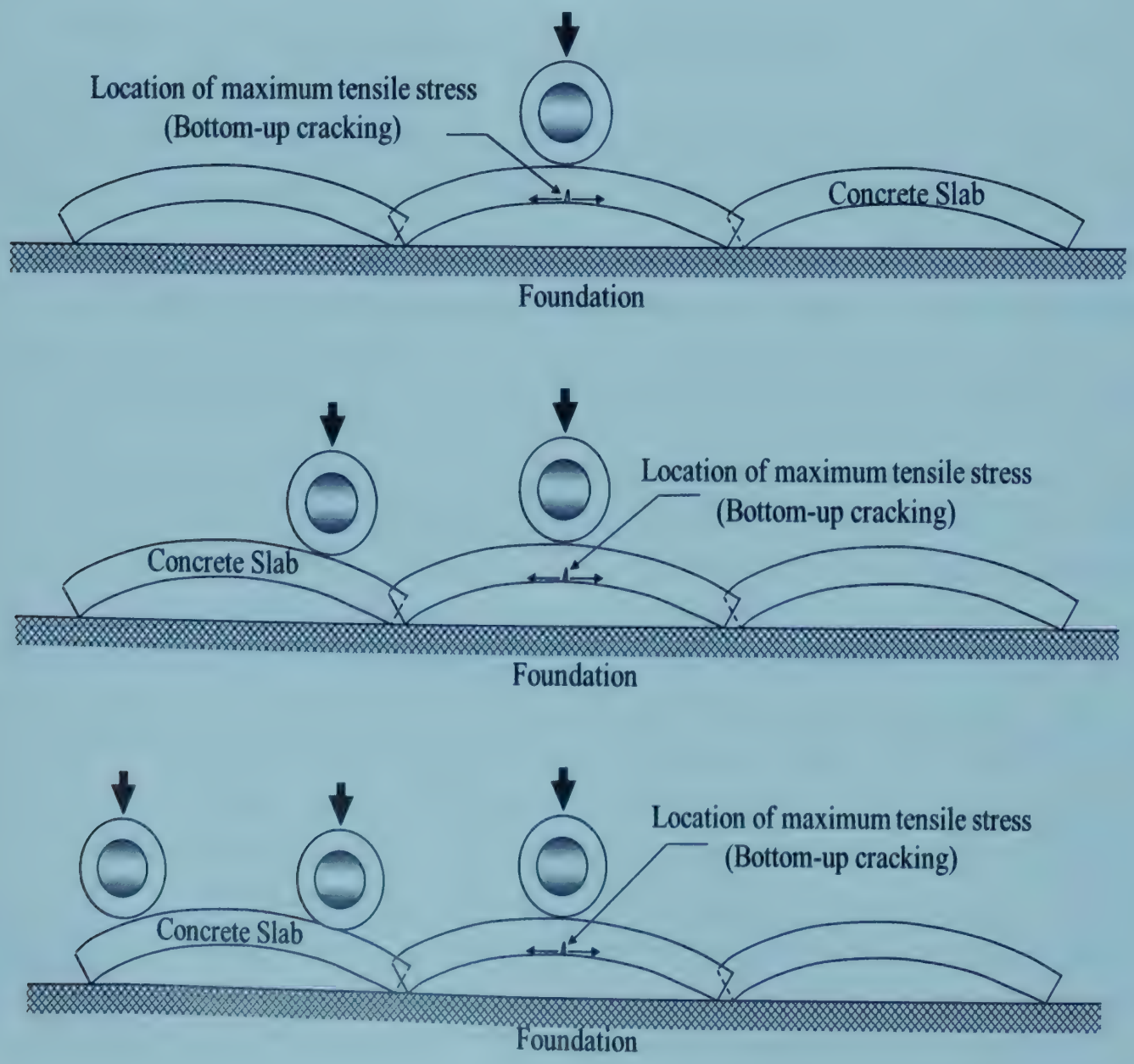


Fig. 6 Critical Load Positions for Single, Tandem and Tridem Axles in the Middle of the Slab during Day Hours

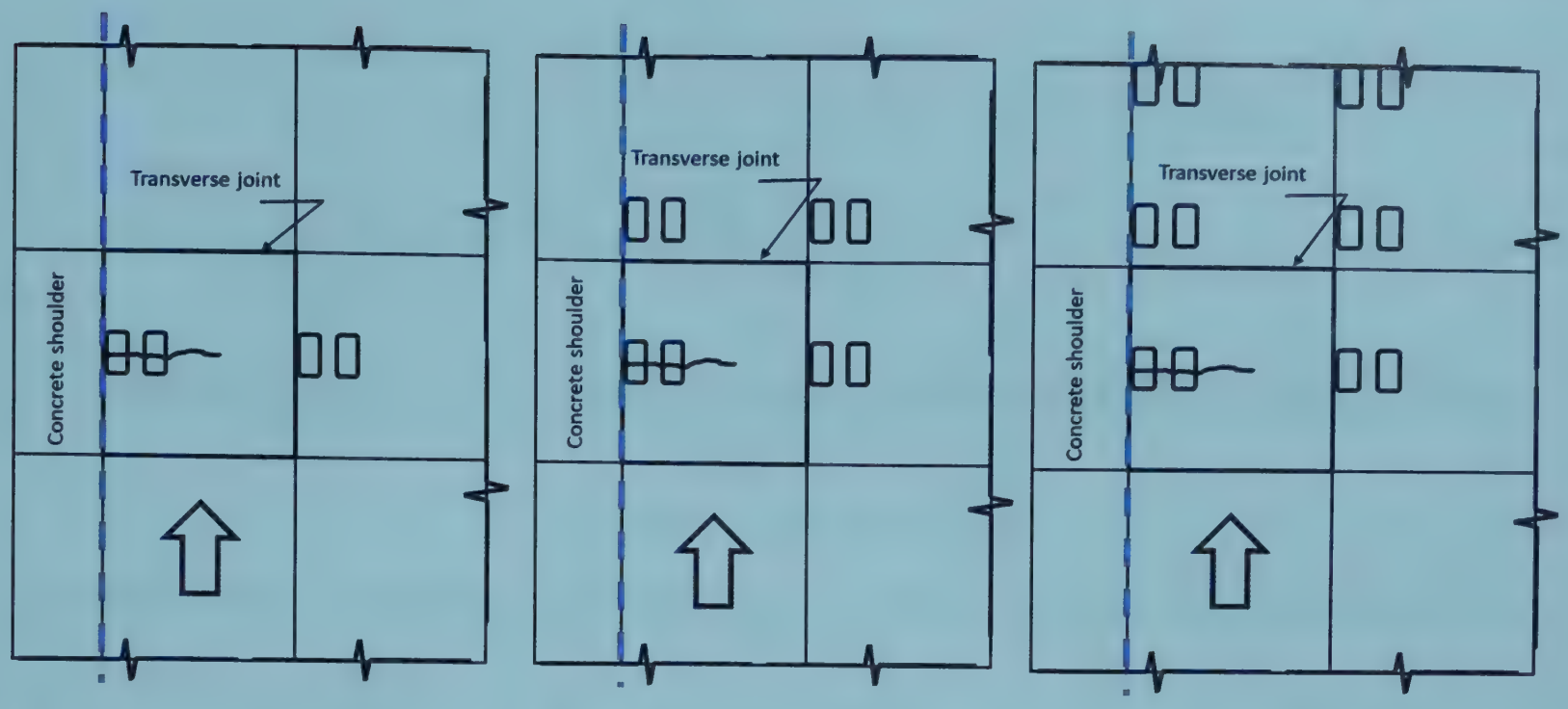


Fig. 7 Typical Critical Load Positions for Transverse Cracking Case with Positive Temperature Differential for Single, Tandem and Tridem Axle Loads for SSCP with Concrete Shoulder

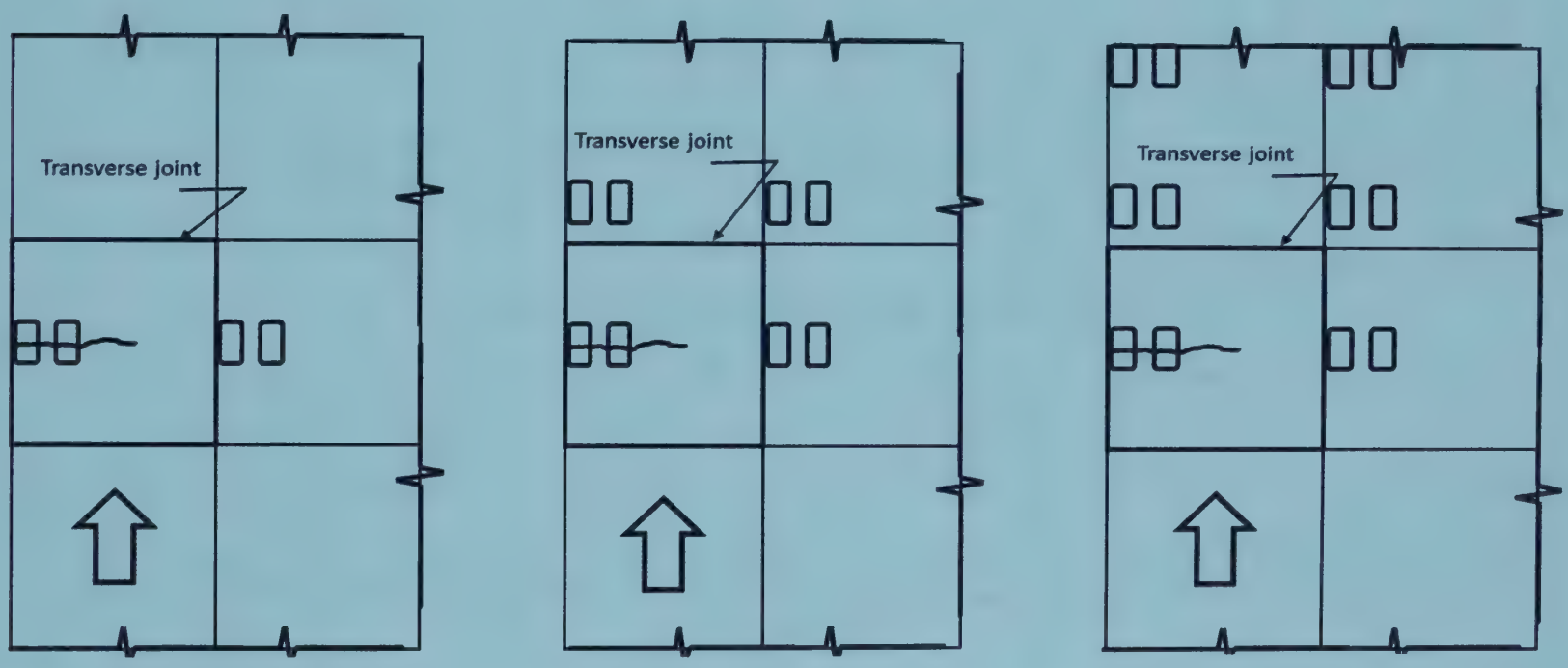
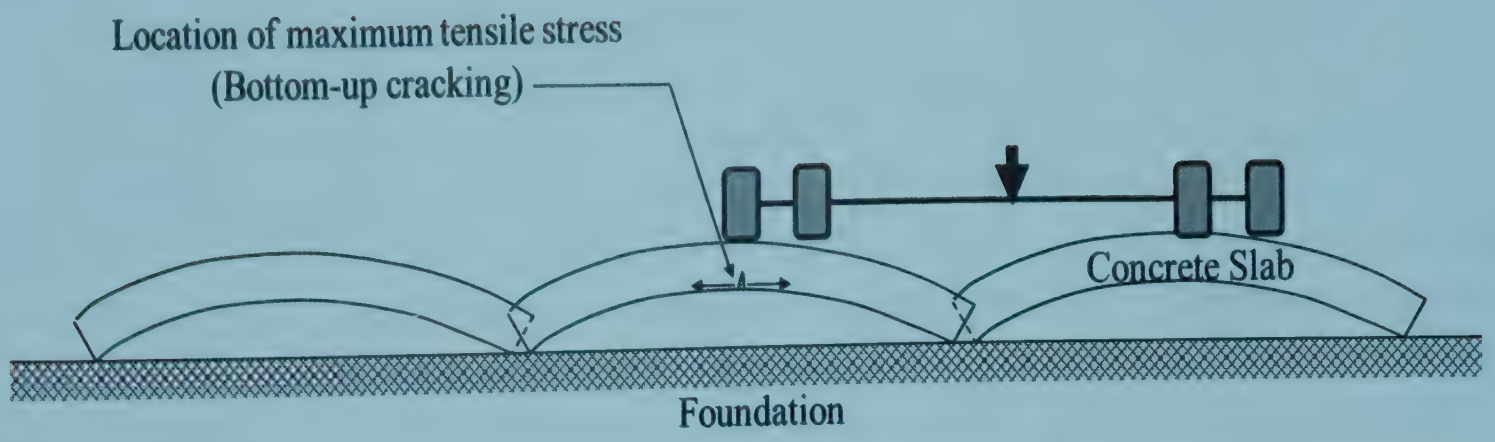
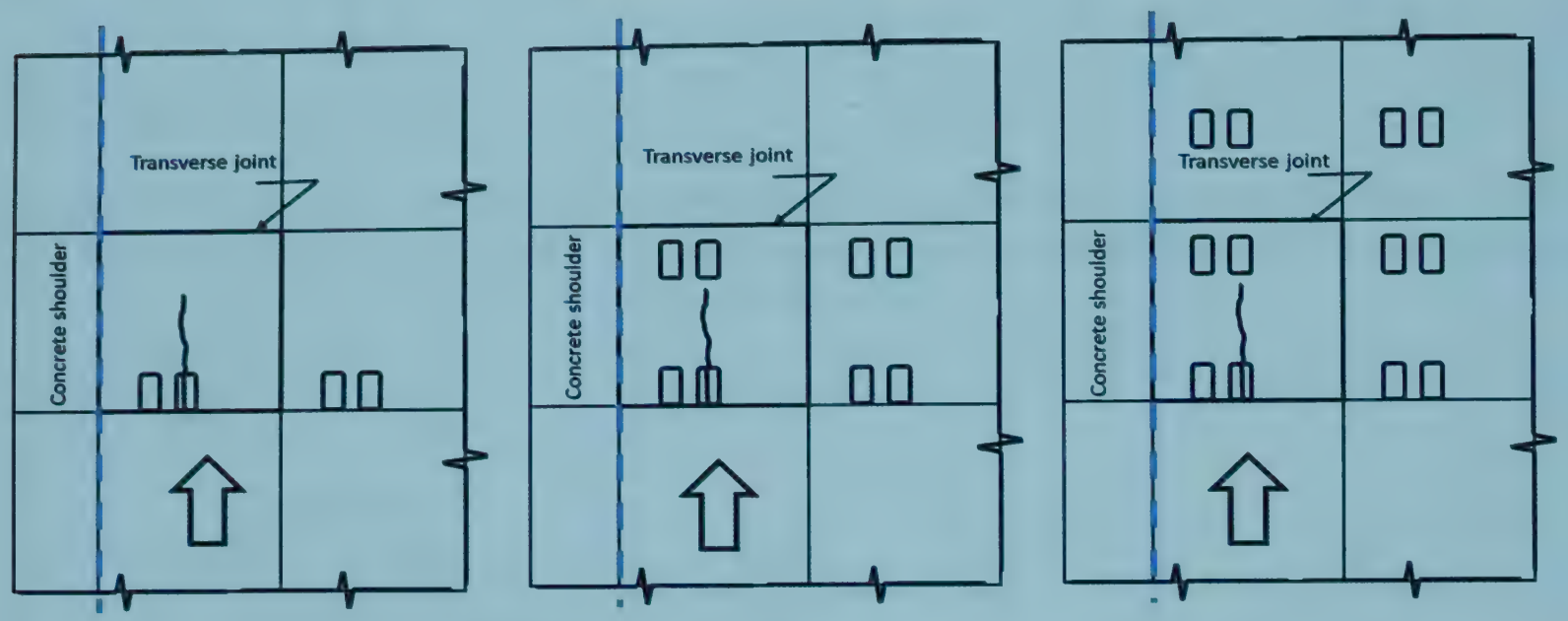


Fig. 8 Typical Critical Load Positions for Transverse Cracking Case with Positive Temperature Differential for Single, Tandem and Tridem Axle Loads for SSCP without Concrete Shoulder

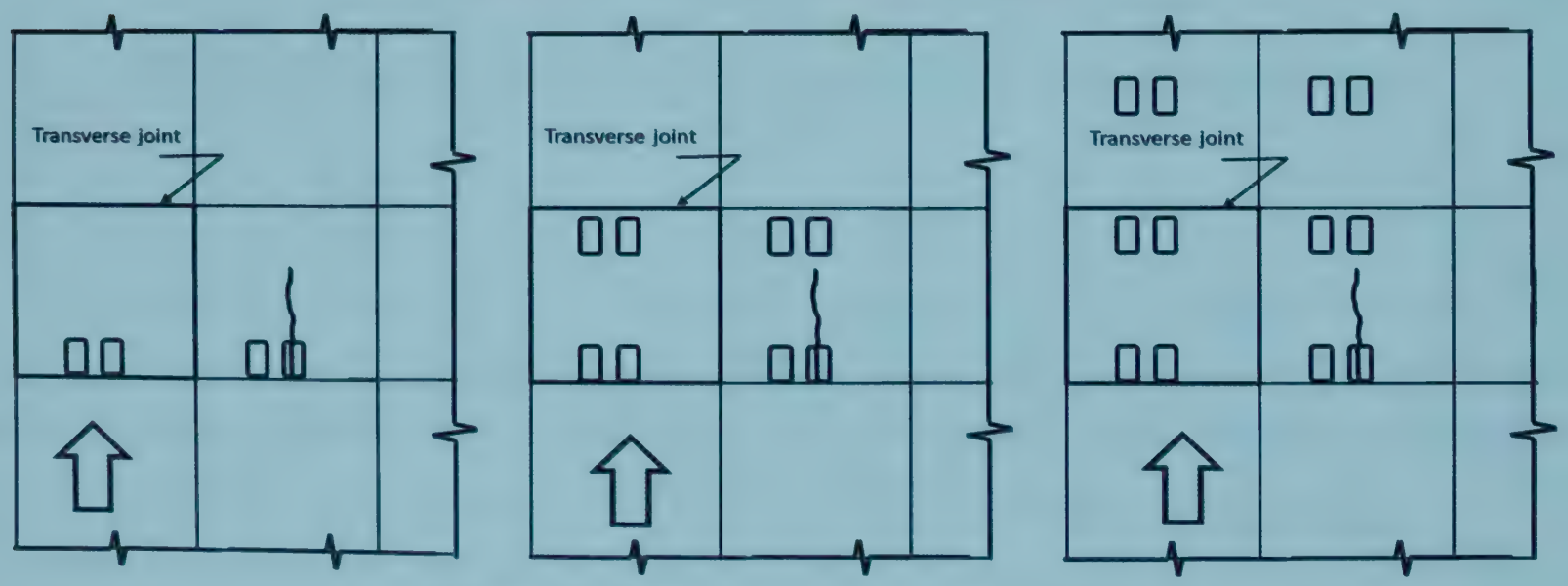
The critical wheel load positions for the longitudinal cracking case with positive temperature differential are presented in **Figs. 9 a, b and c. Fig. 9a** presents the front view of the axle configuration in critical position whereas **Figs. 9b and 9c** represent the plan views of the wheel load configurations causing the maximum stress for the cases for pavements with and without concrete shoulder respectively. In both the types of SSC pavement (with and without concrete shoulder), analysis indicates that the interior slab or the second slab develops maximum tensile stress. Also, there is no significant difference between the magnitudes of the maximum longitudinal stresses obtained with and without concrete shoulder. Hence, the same regression equation has been used for the estimation of longitudinal tensile stress for both the cases (with and without concrete shoulder).



(a) Front View of SSCP



(b) SSCP with Concrete Shoulder



(c) SSCP without Concrete Shoulder

Fig. 9 Typical Critical Load Positions for Longitudinal Cracking Case with Positive Temperature Differential for Single, Tandem and Tridem Axle Loads for SSCP during Day Hours

During the night hours, the top surface is cooler than the bottom surface and the ends of the slab curl up in a concave shape resulting in loss of support for the slab as shown in **Fig. 10.** Due to the restraint caused by self-weight of concrete and partly by the aggregate interlocking along the joints, temperature tensile stresses are caused at the top. **Fig. 11** shows the placement of single, tandem and tridem axle loads close to transverse joints when there is negative temperature

gradient during night period causing high flexural stresses in the top layer leading to top-down cracking. Positioning of axles of different configurations on the slab with successive axles placed close to the transverse joints is shown in **Fig. 10** in side view. These axle positions can initiate Top-Down Cracking (TDC) during the night hours when the pavement has the tendency to curl up. Built-in permanent curl induced during the curing of the concrete slab further aggravates the problem.

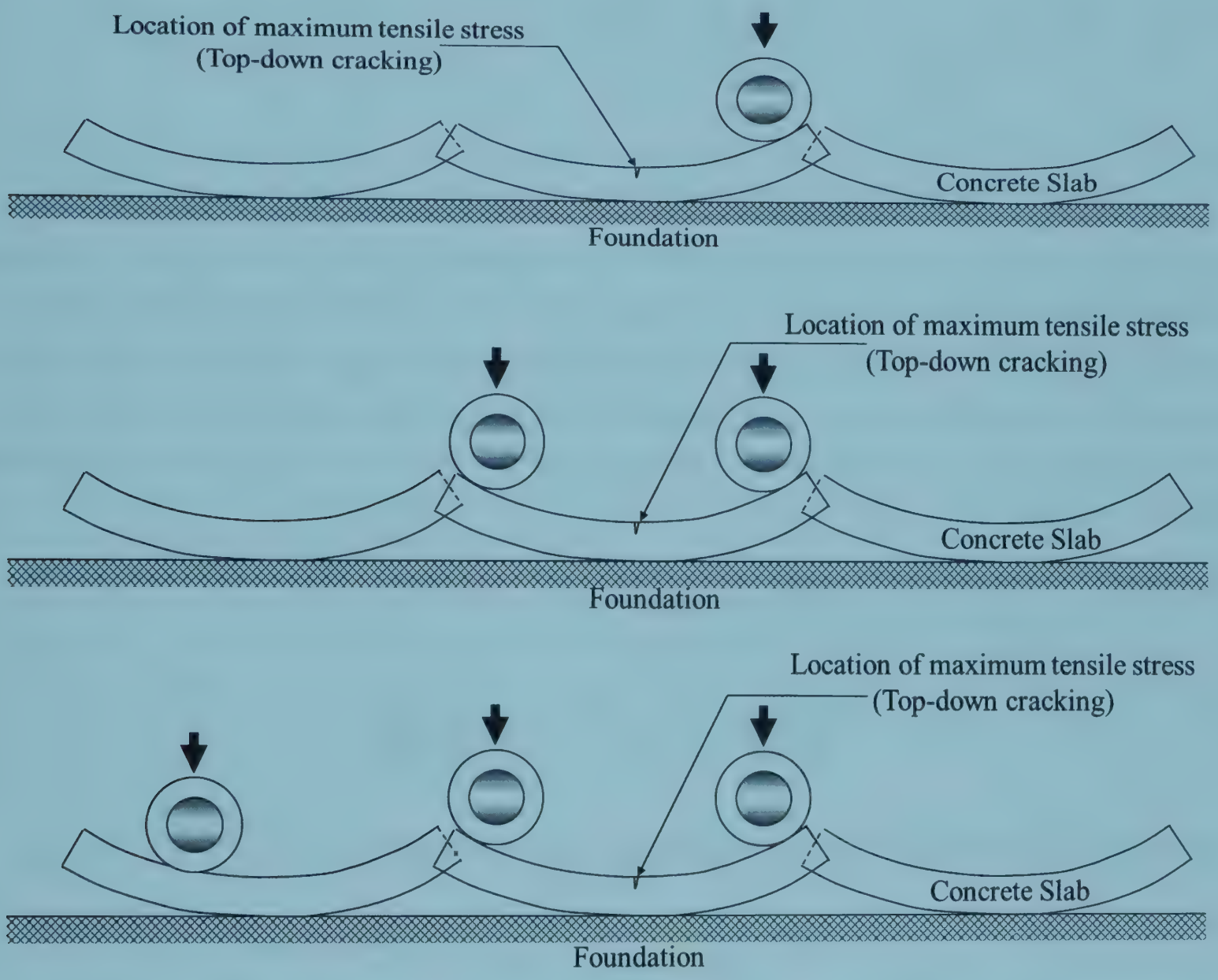
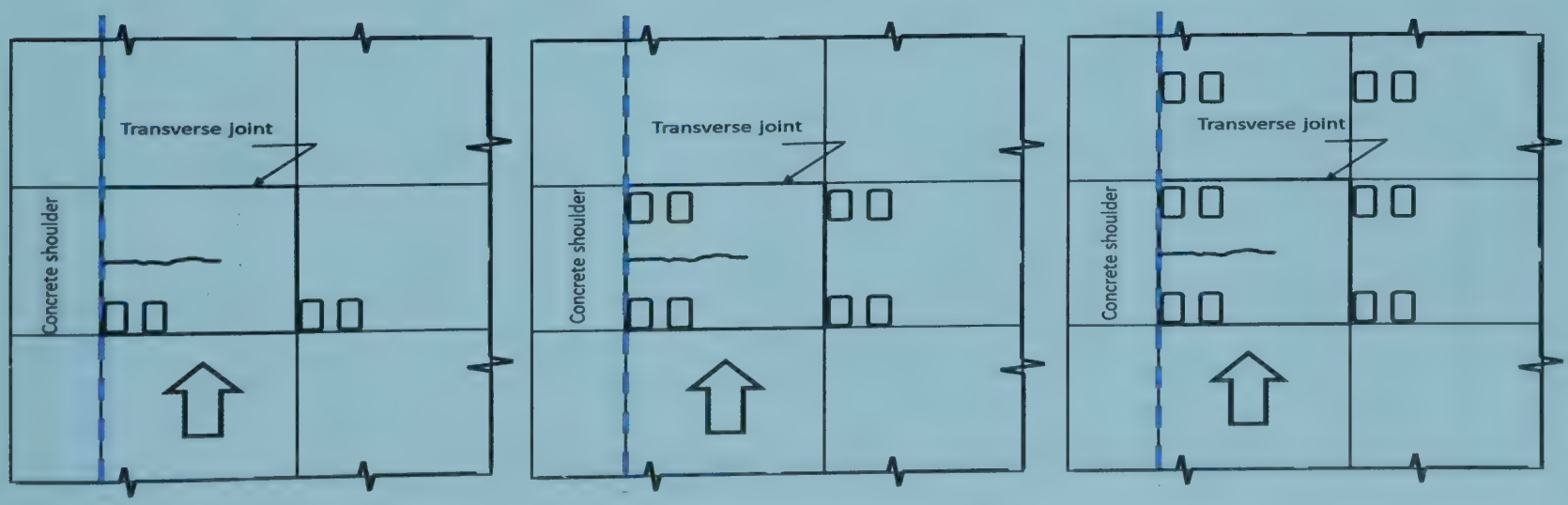
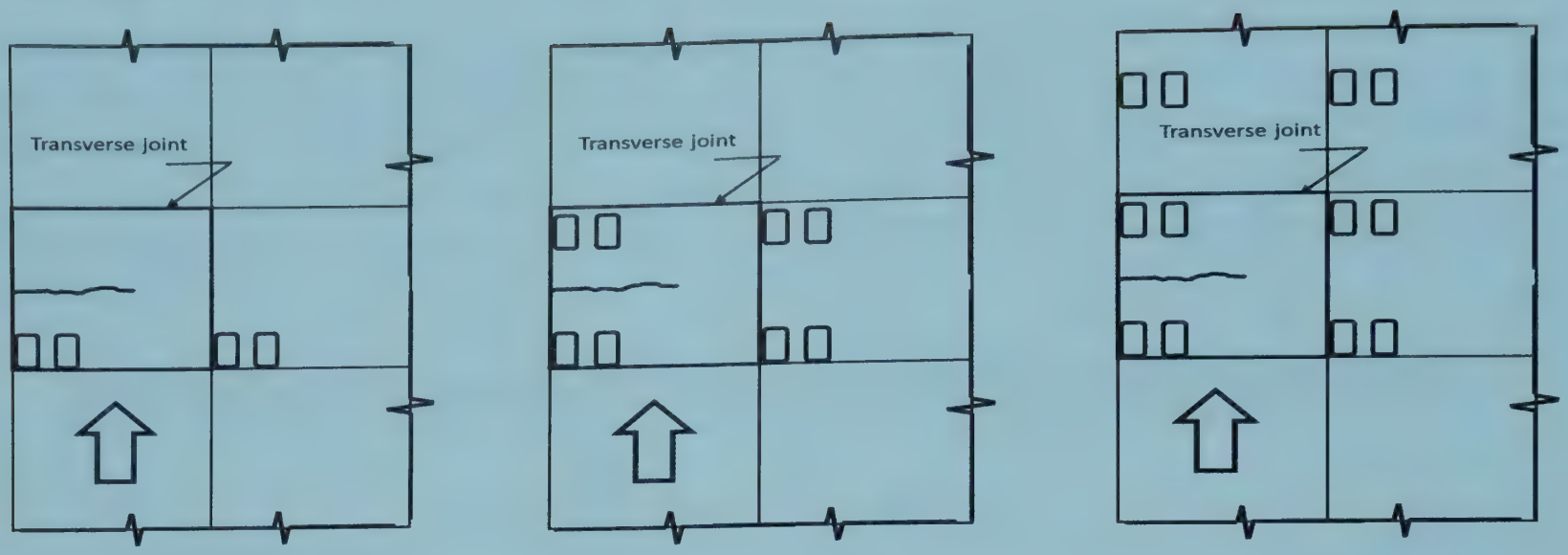


Fig. 10 Critical Load Positions for Rear Single, Tandem and Tridem Axles over SSCP Slab(s) Curled up during Night Hours



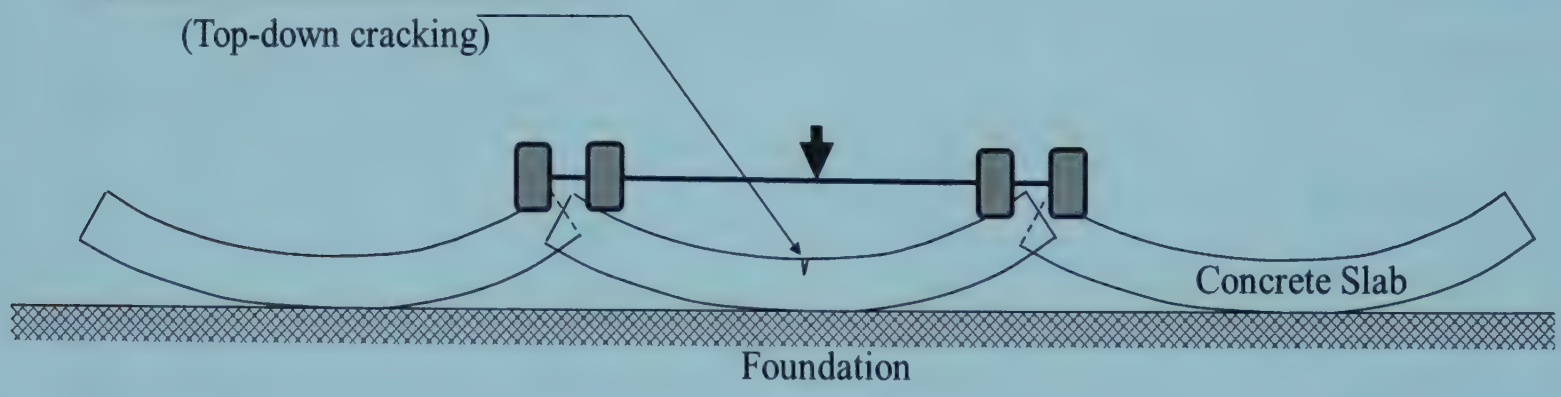
(a) SSCP with Concrete Shoulder



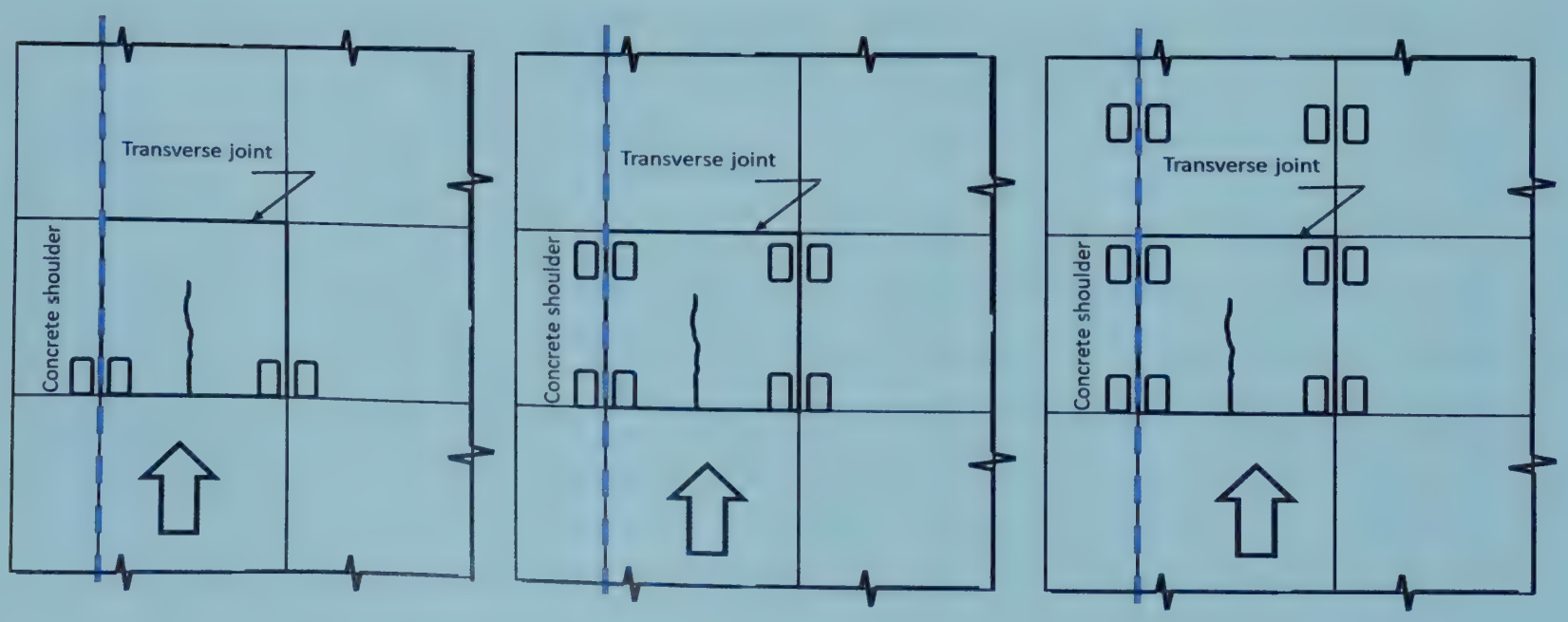
(b) SSCP without Concrete Shoulder

Fig. 11 Typical Critical Load Positions for Transverse Cracking Case with Negative Temperature Differential for Single, Tandem and Tridem Axle Loads for SSCP during Night Hours

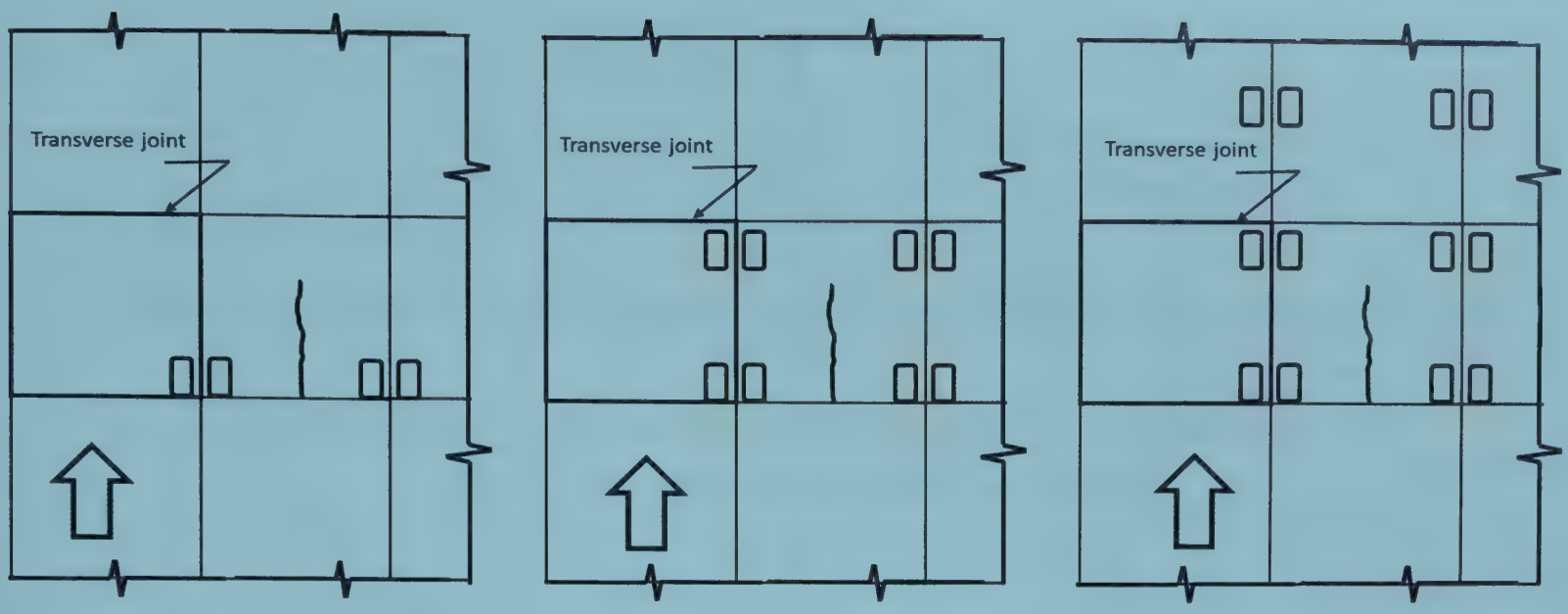
The critical load position for the longitudinal cracking case with negative temperature differential is shown in **Fig. 12a** in front view. This is a representative image with a generalized slab size. **Figs. 12b and 12c** show the plan views of the same for the SSCP with and without concrete shoulder respectively.



(a) Front View



(b) SSCP with Concrete Shoulder

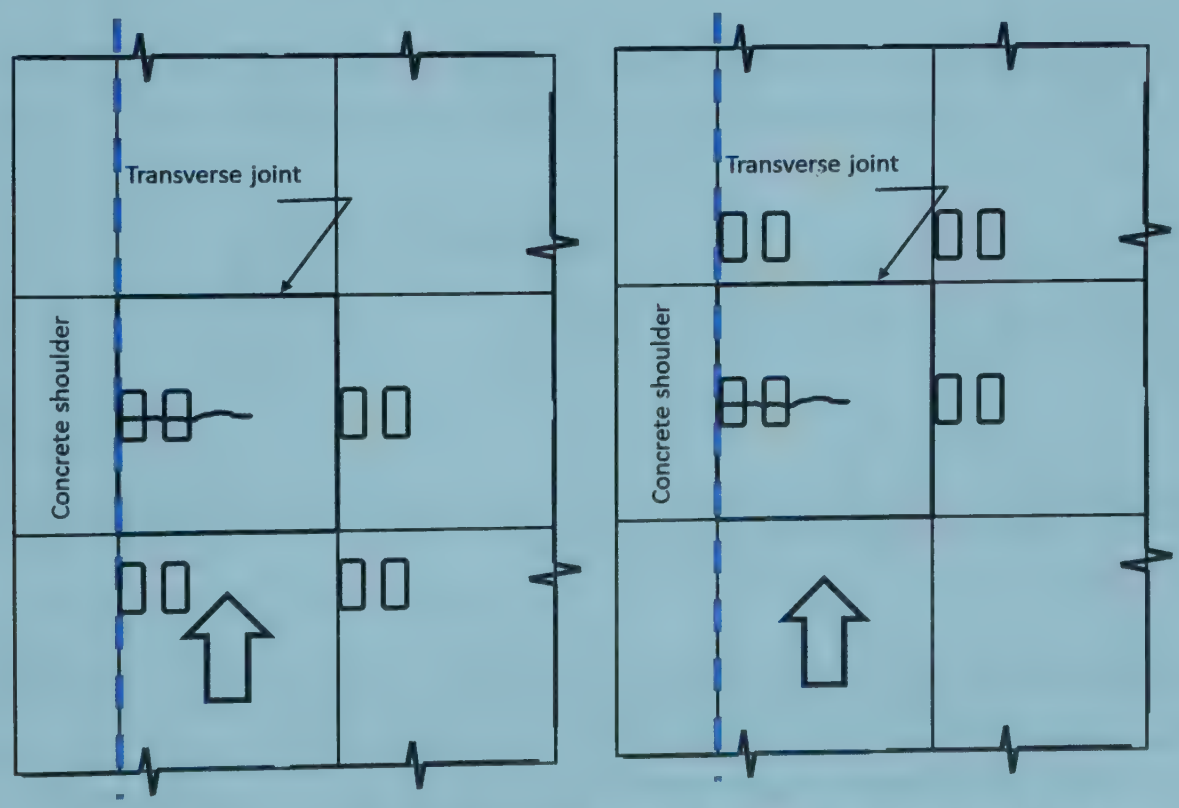


(c) SSCP without Concrete Shoulder

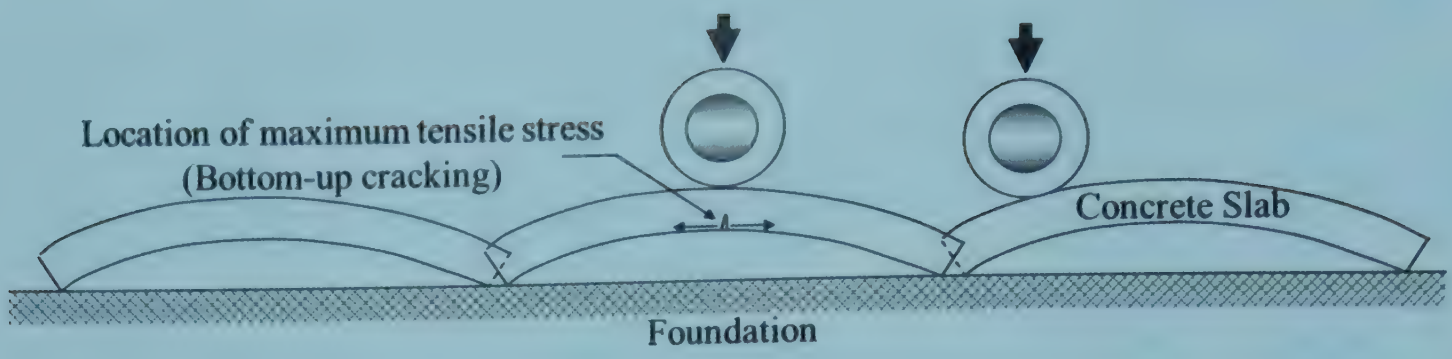
Fig. 12 Typical Critical Load Positions for Longitudinal Cracking Case with Negative Temperature differential for Single, Tandem and Tridem Axle Loads for SSCP during Night Hours

The typical positions of the wheel loads that induce the maximum tensile stress in the short slabs are presented with a generic size of the slab in **Figs. 6 to 12**. The actual critical load positions will be slightly different depending on the size of the slab and the axle spacing and spacing between the dual wheel sets of the same axle.

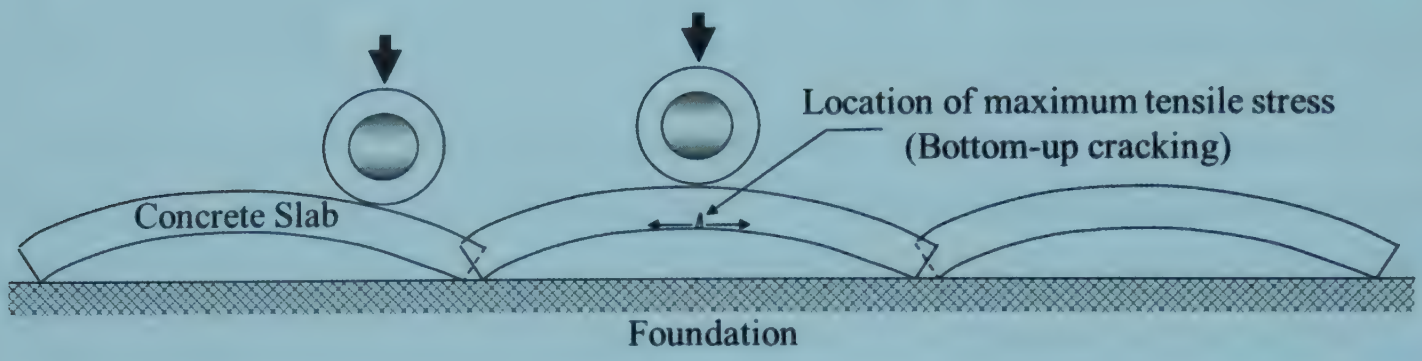
In the case of transverse cracking with positive temperature differential, the tandem and tridem load repetitions must be considered twice as critical stress magnitude is produced in the slab as first and last axles of the tandem or tridem axle units are placed one after the other in the middle portion of the slab. **Figs. 13 and 14** show the placement of tandem axle for SSCP with and without concrete shoulder, respectively.



(a) Two Critical Positions for the same Tandem Axle



(b) First Axle of the Tandem Axle Set on the Slab Considered (traffic direction is from right to left)



(c) Last Axle of the Tandem Axle Set on the Slab Considered (traffic direction is from right to left)

Fig. 13 Illustration of the Placement of First or Last Axles of the Tandem Axle Set at Mid-Slab for Edge Loading Position for Transverse BUC for SSCP with Concrete Shoulder during Day Hours

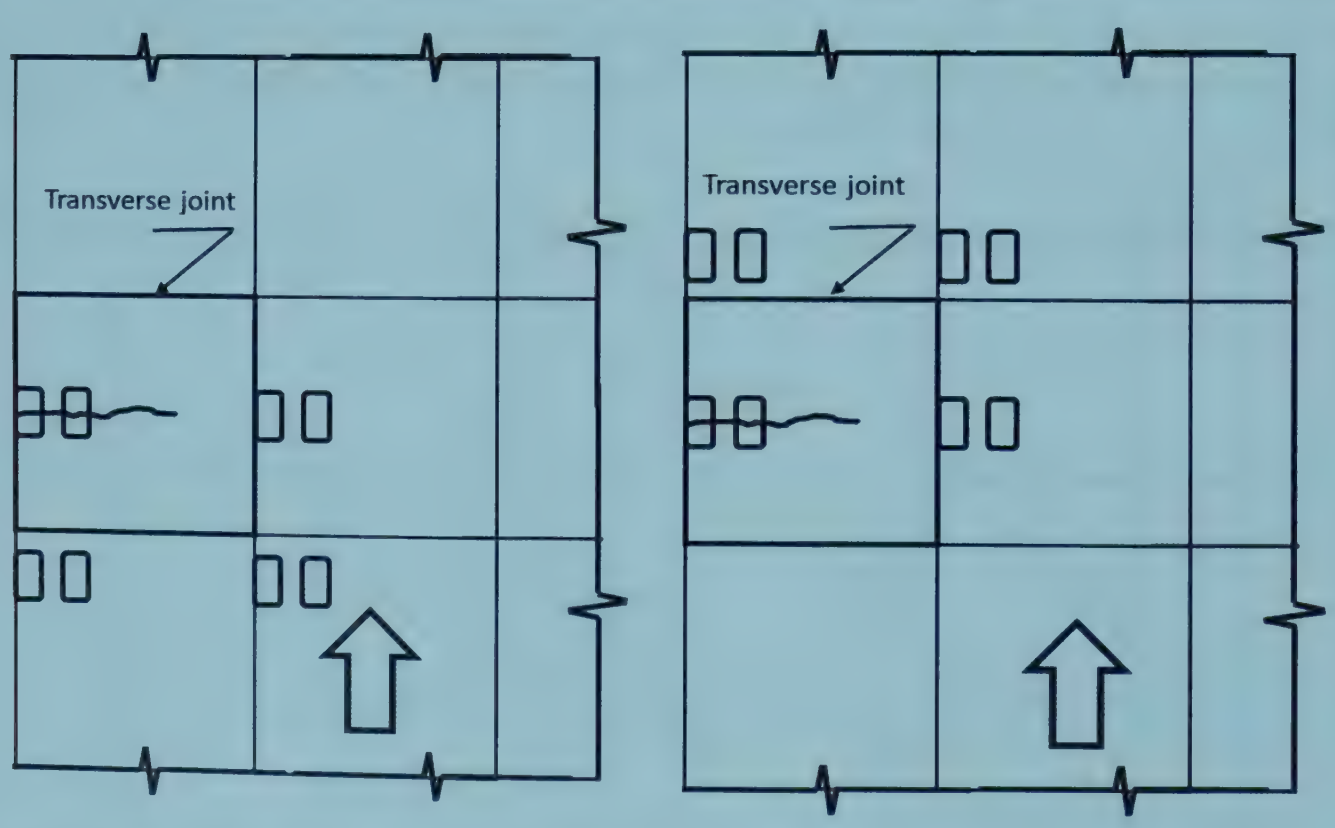
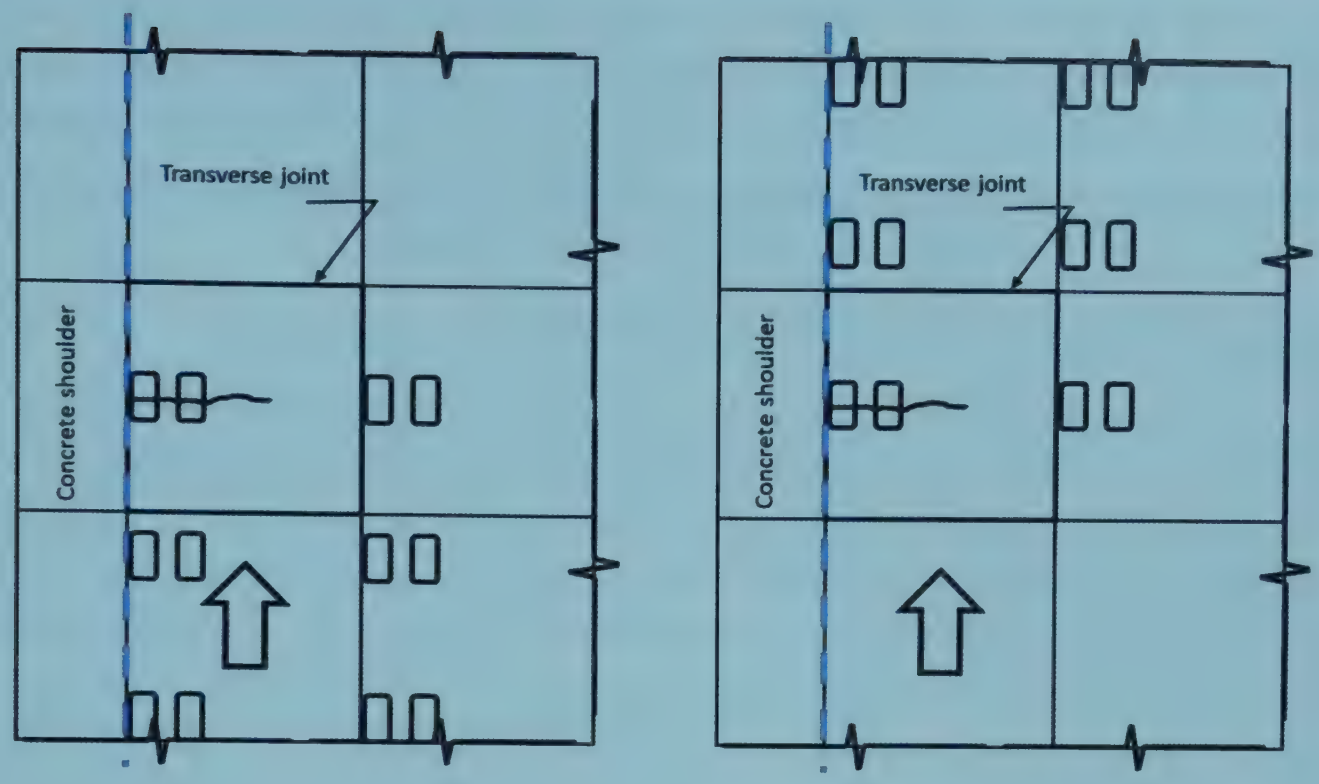
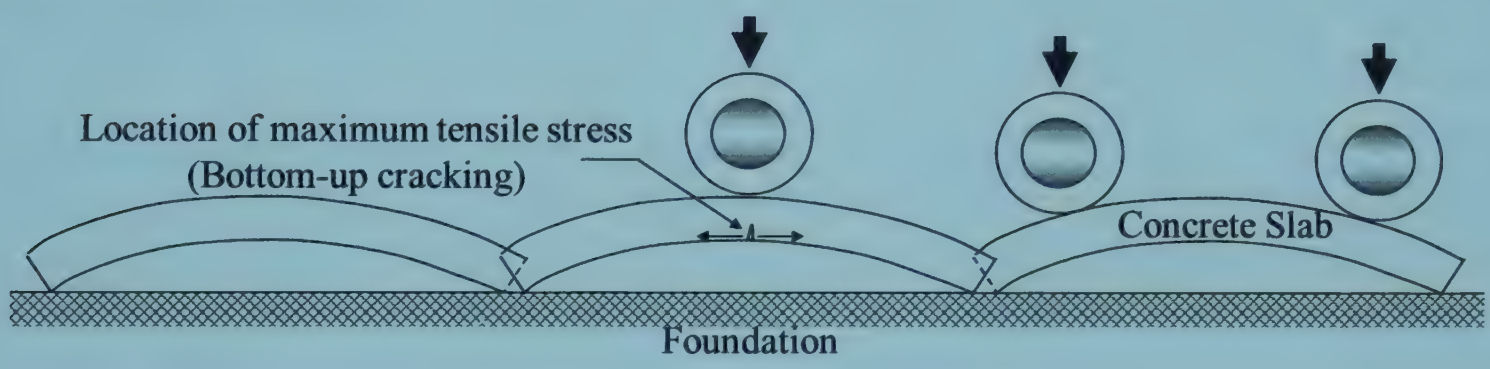


Fig. 14 Load Positions for Maximum Stress in the Short Slab when the First or Last Axle of Tandem Axle Set is at the Mid Length of the Slab in the Case of Transverse BUC for SSCP without Concrete Shoulder during Day Hours

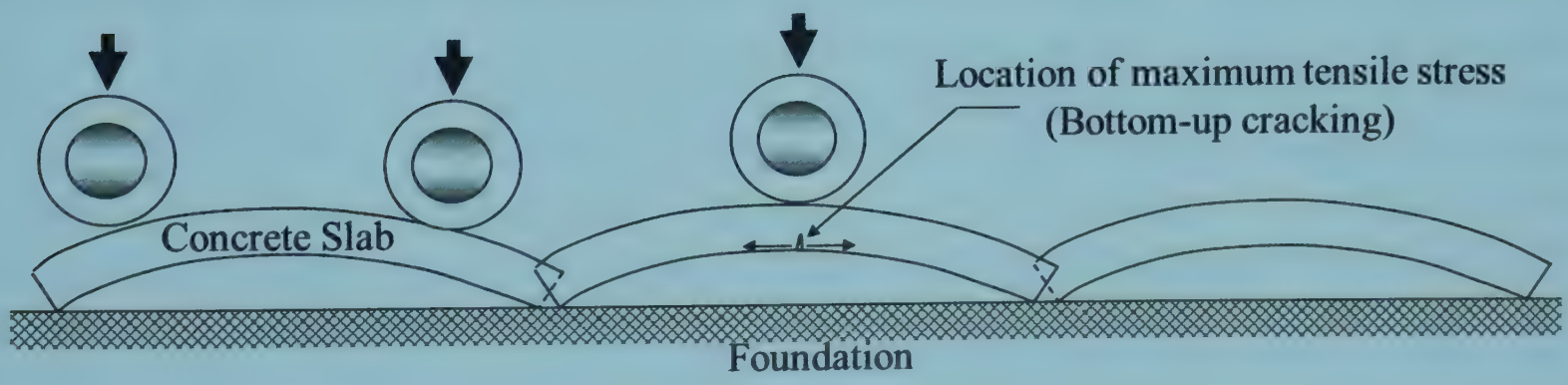
Fig. 15 represents the case of tridem axle in two critical load positions in transverse cracking case with positive temperature differential for the case of SSCP with concrete shoulder, indicating the need for counting the tridem axles twice.



(a) Two Critical Positions for the same Tridem Axle



(b) First Axle of the Tridem Axle Set on the Slab Considered (traffic direction is from right to left)



(c) Last Axle of the Tridem Axle Set on the Slab Considered (traffic direction is from right to left)

Fig. 15 Load Positions for Maximum Stress in the Short Slab when the First or Last Axle of Tridem Axle Set is at the Mid Length of the Slab in the Case of Transverse BUC for SSCP with Concrete Shoulder during Day Hours

The positions of maximum tensile stress, along the length of the slab edge, for transverse, longitudinal and corner top-down cracking, are very close to each other in the case of short slabs and hence can be grouped together. Hence, if the slabs are designed for longitudinal and transverse cracking failures, it would also account for the check to be carried out for corner cracking.

7.3 Analysis of SSCP for Flexural Tensile Stresses

Since the loads causing failure of pavements are mostly applied by single, tandem, tridem and other multiple axles, stresses should be determined for the conditions illustrated in **Figs. 6 to 12**. The IRC:58 flexural stress analysis results are based on the Finite Element (FE) modelling of a single slab resting on Winkler's foundation. That assumption might have been appropriate for the slab size of 3.5 m x 4.5 m. However, as the slab size decreases, the load transfer efficiency of joints plays a major role in distributing the wheel load to the foundation through the adjacent slabs. To account for the load transfer to the adjacent slabs, a multi-slab finite element model is required. In most of the cases, Load Transfer Efficiency (LTE) and Deflection Transfer Efficiency (DTE) are used interchangeably. However, measuring the DTE of a joint using a Falling Weight Deflectometer (FWD) is very simple while measuring the actual LTE is very difficult. In the present study, the value of DTE is considered instead of LTE, as it can be directly measured in the field and can be evaluated in the FE model also.

The IITKGP SSCP-FE model developed at IIT Kharagpur for the analysis of SSCP is a multi-slab finite element model exclusively developed for the finite element analysis of short slab concrete pavements taking into account the Deflection Transfer Efficiency (DTE) of the joints as the SSCPs have more number of joints for a given area of the pavement. The FE analysis is done for a large number of combinations considering 5 different slab sizes, 5 different thicknesses, 5 different modulus of subgrade reaction values, 5 different magnitudes of load and 5 different temperature differential values for a given axle type and direction (positive or negative) of the temperature differential.

Single, tandem and tridem axles were considered separately as the centre-to-centre distance between the individual axles of the tandem/tridem axle (which is typically 1.3 m as assumed in IRC:58 guidelines) affects the magnitude of load induced stress differently for different slab sizes. This is due to the placement or non-placement of the second/third axle of the tandem/tridem axle on the same slab which may increase or decrease the magnitude of stress depending on the direction of temperature differential and the critical position of the load. So, the FE analysis was carried out for each slab size separately with each type of axle for each direction of temperature differential and for each mode of failure (direction of cracking which could be either transverse or longitudinal) considered. The total number of pavement combinations analyzed are listed in **Table 1.**

The presence of concrete shoulder was also considered separately as it too affects the magnitude of stress to certain extent. A Deflection Transfer Efficiency (DTE) of 50 % was found to induce maximum stress in the short slab due to wheel load for the range of thicknesses analyzed. So, a DTE value of 50% was adopted for this analysis. The advantage of taking this condition for analysis is that the stress induced in the slab will always be less than the estimated stress, whether the DTE is higher or lower. So, only joint deterioration may occur over a period of time

and DTE can be partially restored periodically by cement slurry/cement mortar grouting into the joint. Localized foundation failures can be corrected by jack lifting the slab and grouting the mortar into the gap between the foundation and the bottom of the slab.

Table 1 Different Pavement Combinations analysed using Finite Element Technique for SSCP with Concrete Shoulder

Parameter	Combinations
No. of Slab sizes	5
No. of Slab thicknesses	5
No. of Modulus of subgrade reaction (k) values	5
No. of Temperature Differentials (TD)	10 [5 (positive) + 5 (negative)]
No. of Axle types	3 (single, tandem, tridem)
No. of axle loads considered for each axle type	5
No. of slab cracking directions considered	2 (longitudinal and transverse)
Total number of scripts generated and executed	37,500 [5 x 5 x 5 x 10 x 3 x 5 x 2]

The number of combinations analyzed for SSCP without concrete shoulder = 18,750. The total number of scripts generated for the analysis of all the combinations presented in **Table 1** is 56,250 [37,500 for slab with concrete shoulder (longitudinal and transverse cracking cases) + 18,750 for slab without concrete shoulder (only transverse cracking)], excluding the scripts generated for estimating the Deflection Transfer Efficiency (DTE) values for different spring constants (for different slab size, thickness, and modulus of subgrade reaction values to cover DTE range of 10% to 90%) and alternative load position scripts for identifying the critical load positions (which will be another 3000 scripts).

Stress analysis has been done for the following cases:

- Transverse cracking analysis was done for Bottom-Up Cracking (BUC) and Top-Down Cracking (TDC) cases for
  - Pavement with concrete shoulders for single rear axle
  - Pavement without concrete shoulders for single rear axle
  - Pavement with concrete shoulders for tandem rear axle
  - Pavement without concrete shoulders for tandem rear axle
  - Pavement with concrete shoulders for tridem rear axle
  - Pavement without concrete shoulders for tridem rear axle
- Longitudinal cracking analysis was done for Bottom-Up Cracking (BUC) and Top-Down Cracking (TDC) cases for
  - Pavement with concrete shoulders for single rear axle
  - Pavement with concrete shoulders for tandem rear axle
  - Pavement with concrete shoulders for tridem rear axle

It was observed that the magnitude of flexural stress in the slab with concrete shoulder is higher than that in the slab without concrete shoulder due to the support conditions. Every SSCP will have the interior slabs which act like the slab with concrete shoulder and hence for longitudinal cracking analysis, only slab with concrete shoulder case is presented in these guidelines. The results of the Finite Element (FE) analysis have been used for the computation of flexural stresses for pavements without dowel bars and tie bars. Terminal Deflection Transfer Efficiencies (DTE) for SSCP is assumed to be 50% for both transverse and longitudinal joints. This has been done to make design more conservative.

The results of Finite Element (FE) analysis of a large number of concrete pavements with different pavement configurations subjected to various combinations of axle load and temperature differential were generated. The results were used to develop multiple linear regression models. The shape of the slab is considered to be square for the purpose of analysis. The equations can be used to obtain the edge flexural stress caused by a specified magnitude of single/tandem/tridem axle in combination with a selected temperature differential for a given short slab size. The finite element analysis results have been used to develop regression equations for estimation of the flexural tensile stress for bottom-up as well as top-down cracking cases. Separate equations were developed for the bottom-up and top-down cases for transverse and longitudinal cracking cases for different pavement types and foundation strengths. The regression equations are presented in **Appendix-A**. The slab sizes considered for the analysis are given in **Table 2.**

Table 2 Slab Sizes considered for the SSCP Analysis

Size 1	Size 2	Size 3	Size 4	Size 5
1.0 m × 1.0 m	1.25 m × 1.25 m	1.5 m × 1.5 m	1.75 m × 1.75 m	2.0 m × 2.0 m

Multiple regression models were developed for the estimation of the flexural tensile stress for different combinations of pavement, loads and temperature differential.

A few stress charts are presented here as **Figs. 16 to 20** for illustration purpose. The stress comparisons for different slab sizes are presented in the charts shown in **Figs. 21 and 22.**

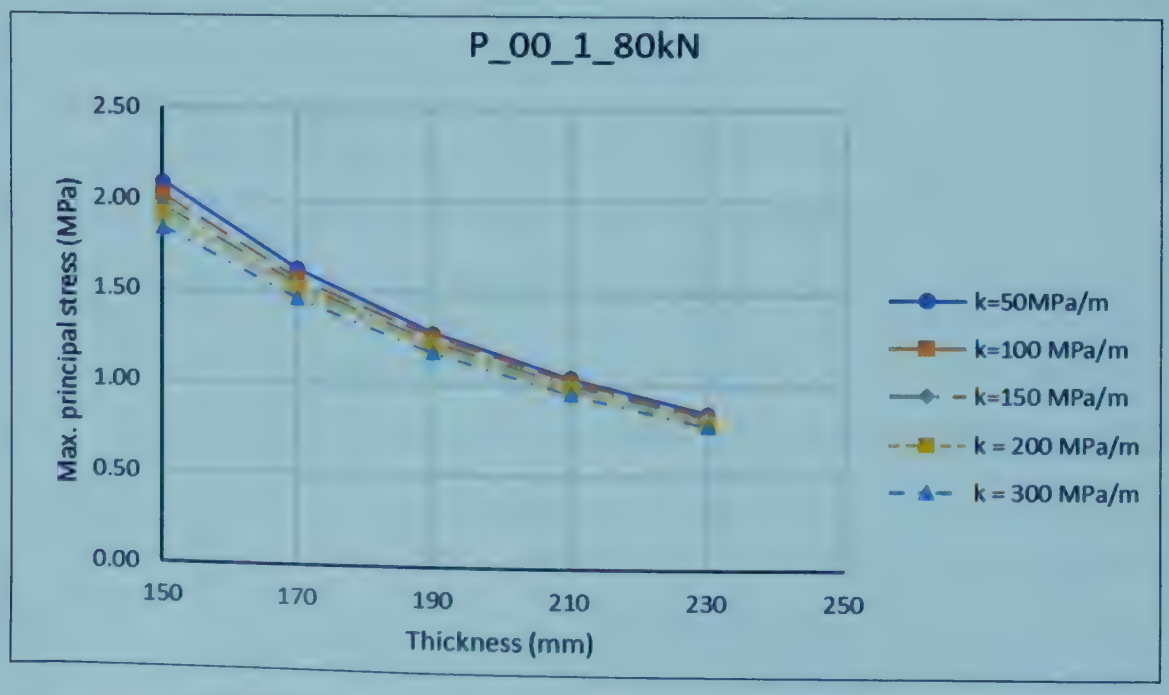


Fig. 16 Stress due to Single Axle Load of 80 kN, Positive ΔT=0 °C, with Concrete Shoulder, Transverse Cracking for the Slab Size of 1.0 m x 1.0 m

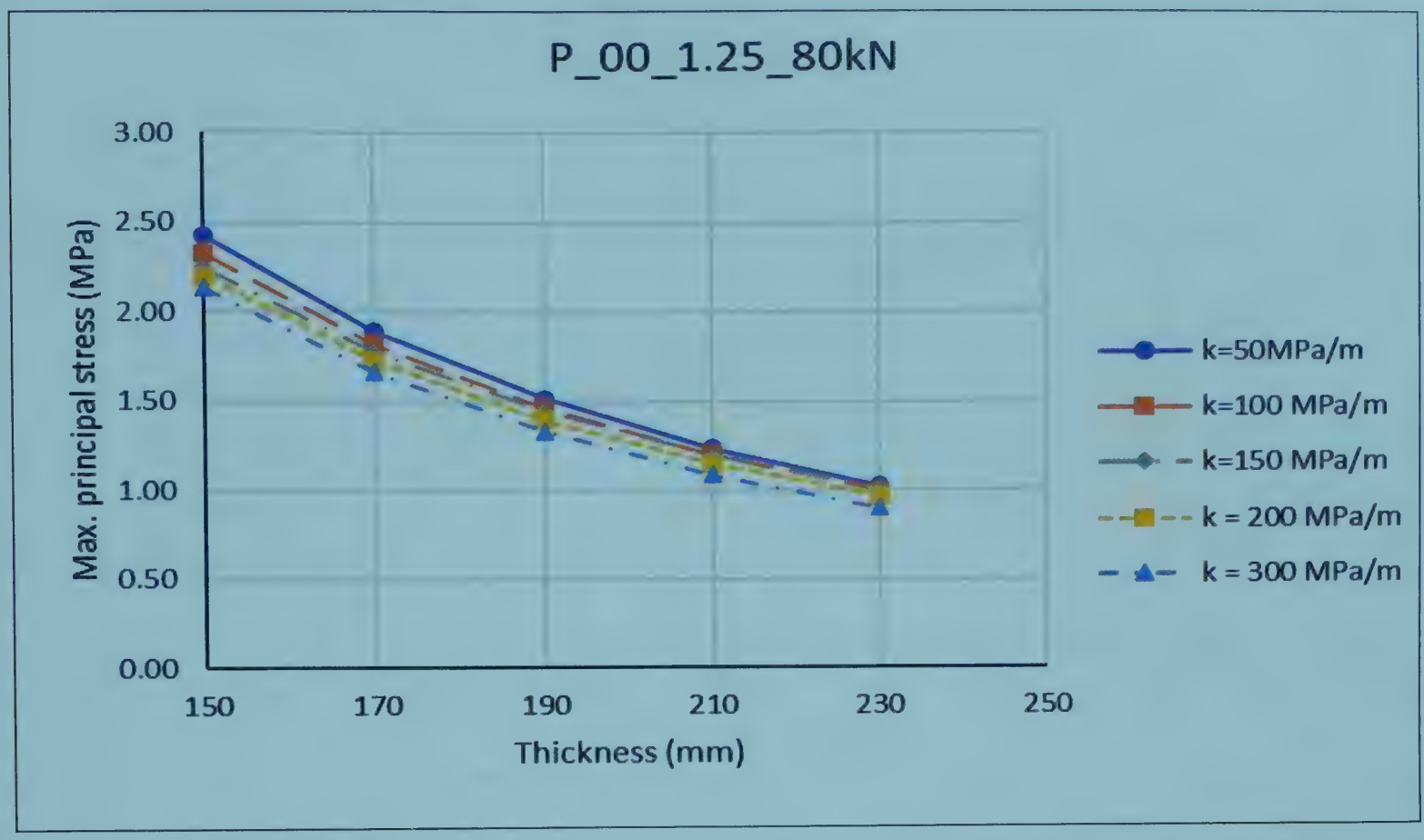


Fig. 17 Stress due to Single Axle Load of 80 kN, Positive ΔT=0 °C, with Concrete Shoulder, Transverse Cracking for the Slab Size of 1.25 m x 1.25 m

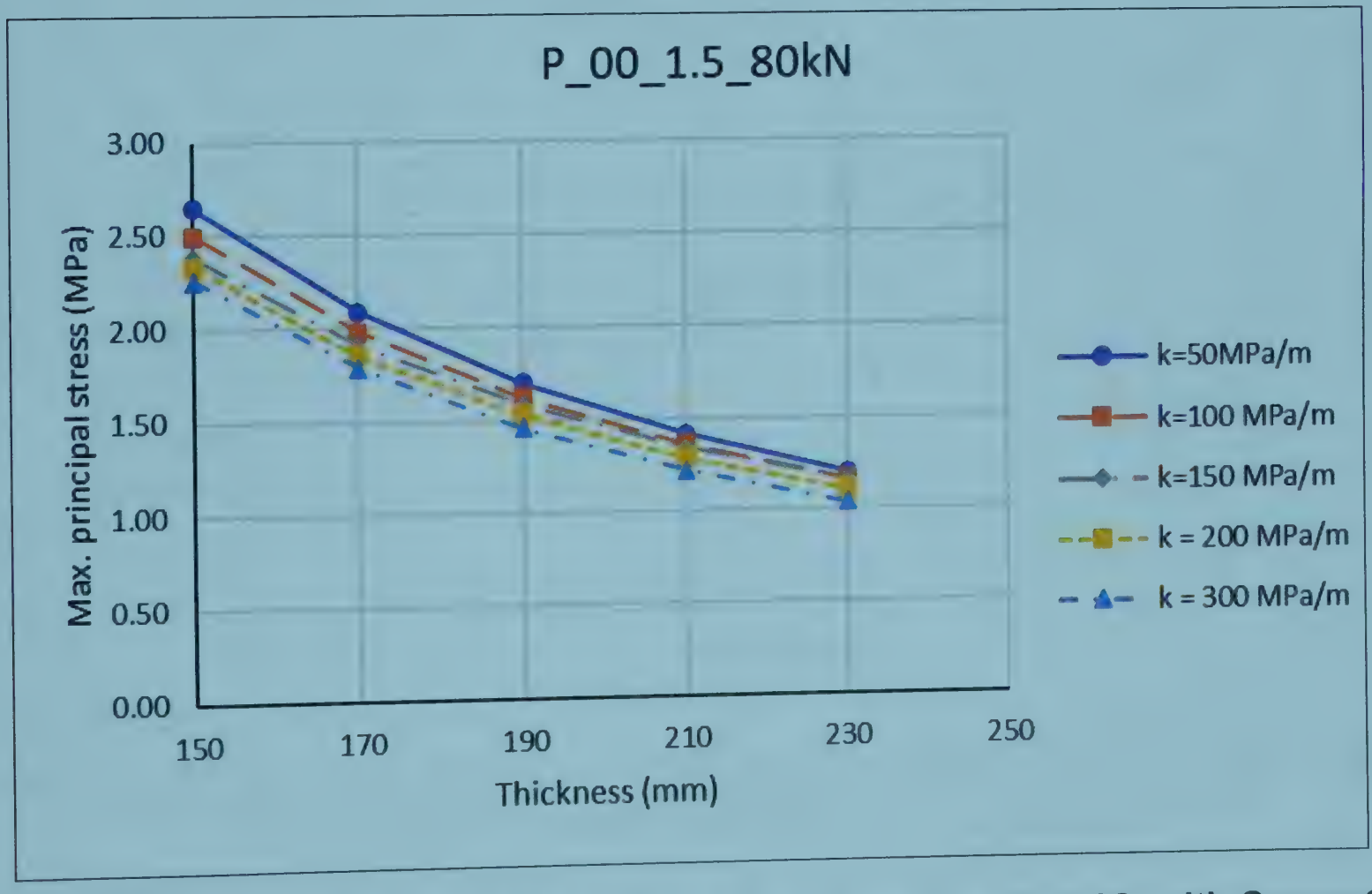


Fig. 18 Stress due to Single Axle Load of 80 kN, Positive ΔT=0 °C, with Concrete Shoulder, Transverse Cracking for the Slab Size of 1.5 m x 1.5 m

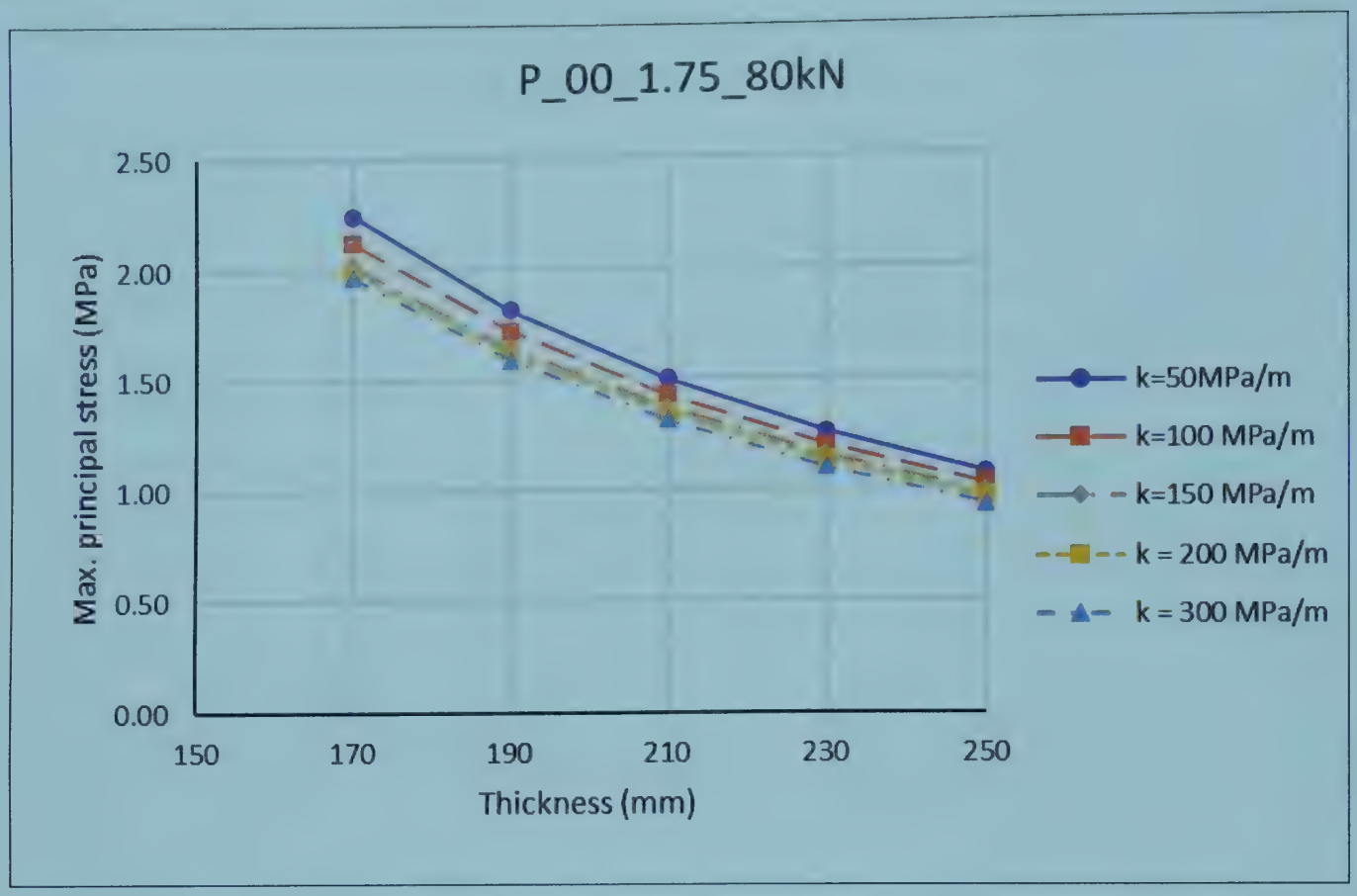


Fig. 19 Stress due to Single Axle Load of 80 kN, Positive ΔT=0 °C, with Concrete Shoulder, Transverse Cracking for the Slab Size of 1.75 m x 1.75 m

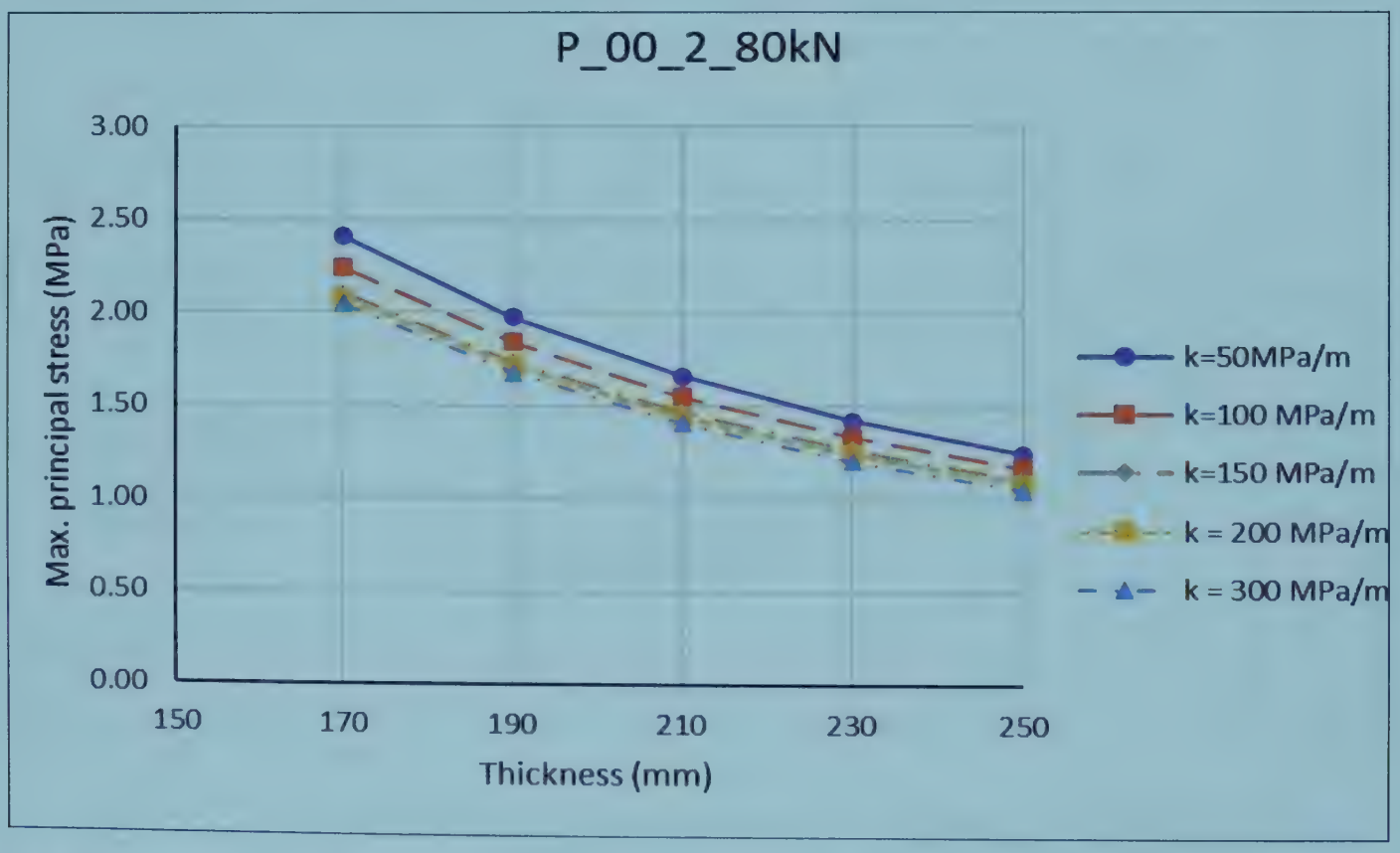


Fig. 20 Stress due to Single Axle Load of 80 kN, Positive ΔT=0 °C, with Concrete Shoulder, Transverse Cracking for the Slab Size of 2.0 m x 2.0 m

The magnitude of stress induced in the slab is dependent on many factors and the most influencing of all are the thickness and slab size as presented in **Fig. 21** for different slab sizes and thicknesses for a modulus of subgrade reaction value of 50 MPa/m at zero temperature differential for transverse cracking under a 80 kN single axle load. It can be observed from **Fig. 21** that the stress increases considerably when the slab size increases. The results for a positive temperature differential of 21 °C for the above-mentioned combinations are presented in **Fig. 22**.

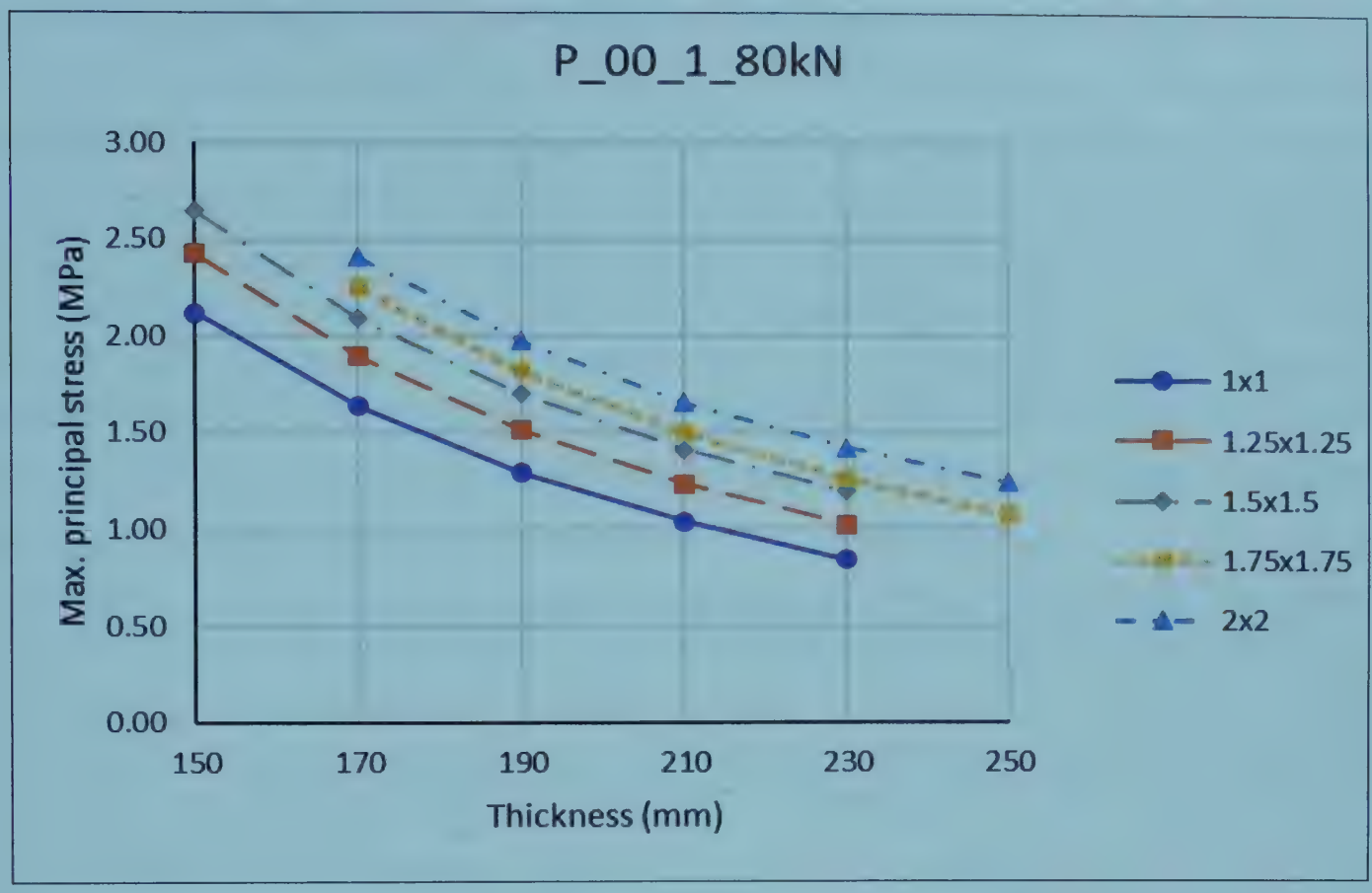


Fig. 21 Variation of Stress for Different Slab Sizes under 80 kN Single Axle at ΔT=0 °C for k- value of 50 MPa/m and with Concrete Shoulder

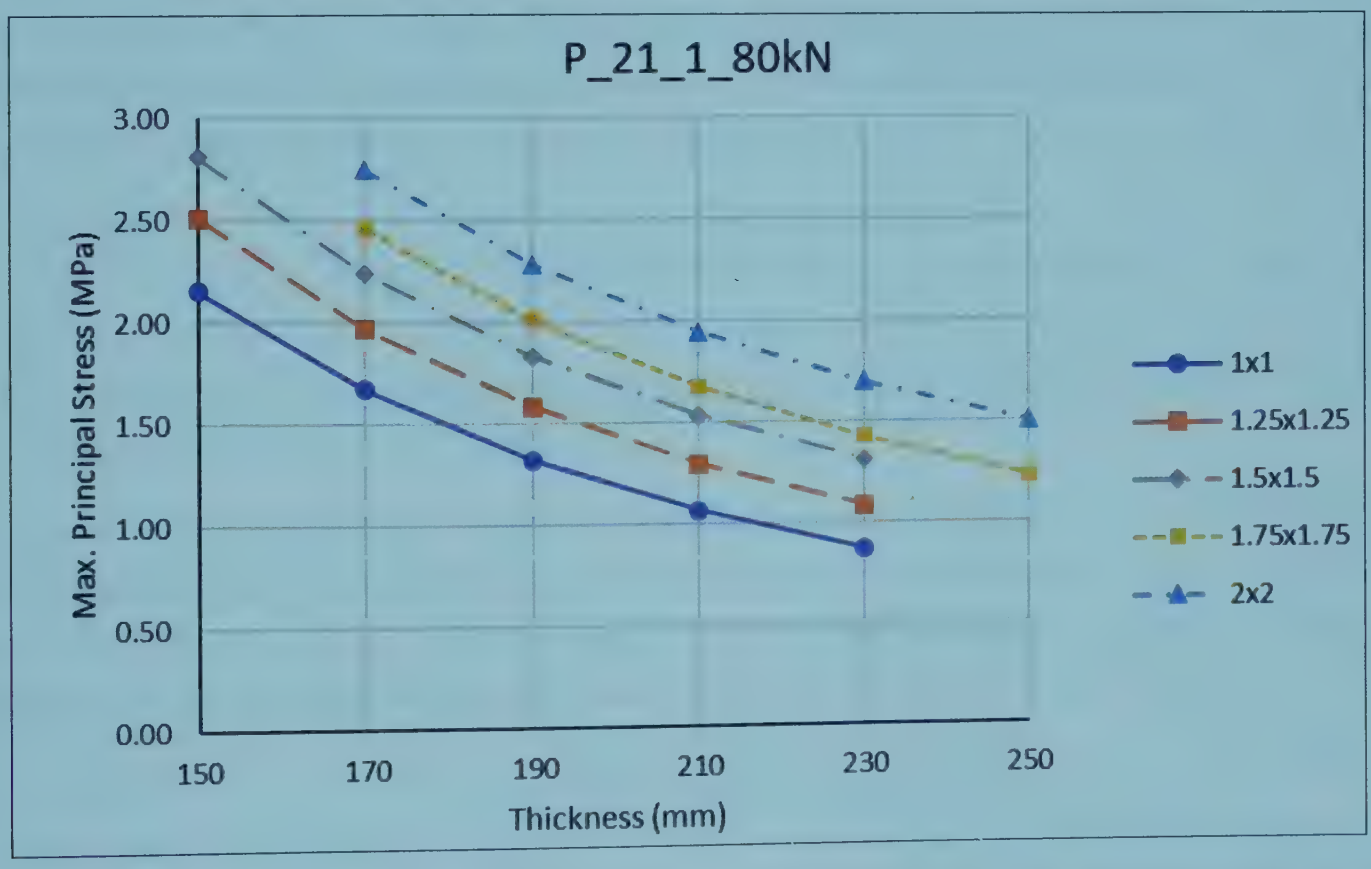


Fig. 22 Variation of Stress for Different Slab Sizes under 80 kN Single Axle at ΔT=+21 °C for k-value of 50 MPa/m and with Concrete Shoulder

7.4 Cumulative Fatigue Damage Analysis

For a given slab thickness and other design parameters, the pavement shall be checked for cumulative bottom-up and top-down fatigue damages. For Bottom-Up Cracking (BUC), the flexural stress at the edge due to the combined action of single/tandem/tridem rear axle load and positive temperature differential is considered. This stress can be found using the regression

equations given in **Appendix-A**. Similarly, for assessing the top-down fatigue damage caused by repeated cycles of single/tandem/tridem axle loads and negative temperature differential, flexural stress can be estimated using the equations given in **Appendix-A**. The flexural stress is divided by the design flexural strength (modulus of rupture) of the cement concrete to obtain Stress Ratio (SR). If the SR is less than 0.45, the allowable number of cycles of axle load is infinity (Equation - 4). For stress ratio values greater than 0.45, allowable repetitions of different axle load groups can be estimated using Equations 5 and 6. The concrete slab undergoes fatigue damage through crack growth induced by repeated cycles of loading. Total cumulative fatigue damage caused to the slab during its service life should be equal to or less than one.

Analysis indicates that the contribution to CFD for bottom-up cracking is significant only during the period between 10 AM and 4 PM because of higher stresses due to simultaneous action of wheel load and positive temperature gradient. Thus, the day time traffic during the six-hour period is to be considered for bottom-up cracking analysis instead of 12-hour traffic. For the top-down cracking analysis, only the CFD caused during the period between 12 mid-night to 6 AM is significant. Hence, the six-hourly night time traffic may be considered for computing CFD for top-down cracking analysis. If the exact proportions of traffic expected during the specified six-hour periods are not available, it may be assumed that the total night time traffic is equally distributed among the twelve-night hours. Similarly, the total day time traffic may be assumed to be distributed uniformly during the twelve-day hours. The Cumulative Fatigue Damage (CFD) expressions for bottom-up and top-down cracking cases are given by Equations 7 and 8 respectively. The time indicated in the equations will vary depending on the geographical location of the project site but the duration of each period may practically remain the same as mentioned in IRC:58 guidelines.

$$CFD\ (BUC) = \sum_i^j \frac{n_i}{N_i}\ (10AM\ to\ 4\ PM) \qquad \text{(Eq. 7)}$$

$$CFD\ (TDC) = \sum_i^j \frac{n_i}{N_i}\ (12\ Mid-night\ to\ 6\ AM) \qquad \text{(Eq. 8)}$$

Where,

N_i = Allowable number of load repetitions for the ith load group during the specified six-hour period

n_i = Predicted number of load repetitions for the ith load group during the specified six-hour period

j = Total number of load groups

7.5 Design Criterion for SSCP

If the sum of the cumulative fatigue damages due to (i) the combined effect of axle load and curling stresses at the bottom of the slab and (ii) the combined effect of axle load and curling stresses at the top of the slab is less than 1, then the pavement thickness may be considered to be safe. This check has to be done separately for transverse cracking case and longitudinal cracking case. In other words, a pavement is deemed to have failed if the sum of Cumulative Fatigue Damages (CFD) due to bottom up and top-down cracking cases is greater than one either in transverse cracking case or in longitudinal cracking case.

The design thickness may be increased by 10 mm to (i) permit re-texturing of the surface twice during the service life and (ii) permit grinding of the surface to rectify faulting, if any, during the pavement service life.

Designers can develop their own excel sheets for analysis and design using the regression equations given in **Appendix-A**. A programmed excel file is available with the guidelines in a Compact Disc (CD) which can be used for thickness design for different trials.

7.6 Recommended Procedure for Design of Short Slab Concrete Pavement

The steps to be followed for design of SSC Pavements are listed below. Solved example for design of SSCP is presented in **Appendix B.**

Step 1 : Stipulate design values for various parameters including short slab size

Step 2 : Select a trial design thickness of pavement slab

Step 3 : Compute the repetitions of axle loads of different magnitudes and different categories expected during the design life

Step 4 : Find the proportions of axle load repetitions operating during the day and night (six-hour) periods

Step 5: Estimate the axle load repetitions for the six-hour-period during the day time. The maximum temperature differential is assumed to remain constant during the 6 hours for analysis of bottom-up cracking.

Step 6: Estimate the axle load repetitions in the six-hour period during the night time. The maximum negative temperature differential during night is taken as half of the day-time maximum temperature differential. A built-in negative temperature differential of 5^0C developed during the setting of the concrete is to be added to the absolute value of negative temperature differential for the Top-Down Cracking (TDC) analysis.

Step 7: Compute the maximum flexural stresses at the critical locations due to the single, tandem and tridem axle loads for the combined effect of axle loads and positive temperature differential during the day time. Determine the stress ratio (Flexural stress/Modulus of Rupture) and evaluate the Cumulative Fatigue Damage (CFD) for single, tandem and tridem axle loads.

Step 8 : Compute the maximum flexural stress in the top surface of the pavement slab due to single, tandem and tridem axle loads under negative temperature differential. Determine the stress ratio and evaluate the CFD for different axle loads for the analysis of top-down cracking for the selected slab thickness.

Step 9: The sum of CFD for the BUC (Step 7) and TDC (Step 8) has to be evaluated for transverse cracking case and longitudinal cracking case separately. If the sum of CFD for BUC and TDC is less than 1.0 for transverse cracking, then the slab thickness is safe against fatigue cracking for transverse cracking. Similarly, the sum of CFD for BUC and TDC should be less than 1 for the longitudinal cracking for the slab thickness to be safe for longitudinal cracking.

Note : *The maximum positive temperature, which depends on the thickness of the slab, may be selected appropriately for each slab thickness considered in the analysis/design process.*

The slab thickness requirement is marginally less when concrete shoulder is provided compared to the case with no concrete shoulder. However, for few cases where the 'k' value is higher (> 200 MPa/m) and the slab size of 1.5 m (barely accommodating the tandem axle), the thickness requirement for with concrete shoulder case could be equal to or nominally (2-5 mm) higher than the design thickness for without concrete shoulder case. This is due to the stiffer support conditions and the additional support offered by the shoulder (slab) near the mid length of the slab when there is a higher negative temperature differential and in the presence of higher proportion of tandem axles. So, to be on the conservative side, the higher thickness (of with concrete shoulder) has to be adopted when the 'without concrete shoulder' case is analyzed (as the second slab from the edge acts like a slab with concrete shoulder). [Tandem axle case of **Fig. 10** may be referred for a better visualization of this particular case with negative temperature differential]

So, as a general rule, when a slab without concrete shoulder has to be designed, the analysis should to be carried out for both with and without concrete shoulder cases. Higher of the two thickness requirements will have to be provided for the without concrete shoulder case.

The entire design process is programmed in an excel sheet and is included in a Compact Disc (CD) enclosed with this document. This will enable the designer to make different trials for arriving at an appropriate design. The designer has to provide modulus of the subgrade reaction of the foundation supporting the pavement slab, 28-day flexural strength of concrete, temperature differential, traffic data such as rate of traffic growth, axle load spectrum, proportion of single, tandem and tridem axles. All relevant traffic and material data have to be given as inputs to the SSCP design excel sheet selected for the size of the slab under consideration, with or without concrete shoulder. A total of 10 design excel files are given in the CD for the design of SSCP with the 5 standard size square slabs for with/ without concrete shoulder cases. Two additional design excel sheets are given, one for the design of rectangular slabs and another for the design of square slabs with intermediate size between the set of standard slab sizes with interpolated magnitudes of stresses.

7.7 Design of Slab with Intermediate Size

If the slab size selected for the SSCP is an intermediate slab size (between any two successive slab sizes for which design sheets are available), then the stresses for the intermediate slab size may be obtained by linear interpolation using the stress values available for the two slab sizes which are nearest to the selected size. For example, if design has to be done for a square slab size of 1.13 m, the magnitudes of stresses have to be interpolated from the stresses calculated for 1.0 m size and 1.25 m size (for which regression equations are available) and cumulative damage analysis is to be carried out using the interpolated stresses.

7.8 Design of Rectangular Slabs

The analysis carried out in these guidelines is for square slabs. However, if a rectangular slab is selected, the design has to be done in two stages. The length of the longitudinal edge (L) has

to be considered for transverse cracking analysis. The length of the transverse edge (W) has to be considered for longitudinal cracking analysis. This approach can be used if the aspect ratio (longer edge length/shorter edge length) is less than 1.2. If the slab size selected for the design is of a rectangular slab of size L × W, then the transverse cracking and longitudinal cracking analysis have to be carried out for two different sizes (L and W respectively). An excel file is included in the CD for design of rectangular slabs. The stresses for transverse cracking analysis and longitudinal cracking analysis have to be copied from the design excel sheets of the two square slab sizes; L and W.

7.9 Joint Activation Requirement in SSCP

In the case of conventional jointed plain concrete pavements, the joint grooves are cut at regular intervals so that the joints (full depth shrinkage cracks) form at those locations. This prevents formation of random cracks. However, all the places where joint grooves are cut do not form into a full depth crack. Only if the crack occurs at the joint groove, then it is called an active joint as it acts as a joint only then. If the joint groove is not active, then it is not a joint (active joint) and hence the effective length of the slab will be more than the length considered in the design. Hence, the stress could be more than anticipated (due to longer span), leading to random cracking in the slabs due to wheel loads (in combination with the temperature stresses). Higher the percentage of active joints, better will be the performance of the concrete pavement.

In the case of SSC pavements, the percentage of active joints is typically 60-70 % compared to a conventional concrete pavement which has nearly 90-95% active joints (Chen et al., 2022). Considering this, extra care has to be taken to increase the percentage of active joints. One such method of activating more joints is by allowing a loaded truck to ply on the pavement section with the wheels placed over the longitudinal joint and then along the mid-width of the slabs after 5-7 days of curing. This process can improve joint activation as the concrete does not attain full strength in 5 to 7 days and the thickness of the PQC layer below the joint groove cut is only 2/3rd of the slab thickness.

7.10 Joint Sealant Requirements

In SSCP, joint sealant is generally not necessary as the joint groove width is less than 5 mm as there is only a single saw cut with a blade of width 3-4 mm. However, if the project site is in a high rainfall area, suitable joint sealant may be used based on the experience of the engineer concerned.

7.11 Design of Dowel Bars

Dowel bars are provided in SSC pavements only for construction joints. The design of the bars shall be done as per IRC:58 guidelines. Considering the smaller sizes of the slabs with closer spacing between the longitudinal joints used in SSCP, the number and spacing of the dowel bars shall be selected so that adequate cover is available to the bars from the longitudinal joints (vertical crack propagation at the joint grooves). So, a minimum cover of half the slab thickness may be provided for the dowel bars.

8. CONSTRUCTION AND EVALUATION OF SSCP TEST SECTIONS ON NH-18

Brief description of the construction of different layers of SSCP test sections are presented in **Appendix-C**. In addition to this, some important observations from the evaluation of the test sections carried out seasonally using the Falling Weight Deflectometer (FWD) to gather information about Deflection Transfer Efficiency (DTE) or Load Transfer Efficiency (LTE) of joints and the functional evaluation carried out using a Network Survey Vehicle (NSV) are also presented in the appendix.

Appendix-A

Regression Equations for Analysis of SSCP

The regression equations have been developed separately for each slab size and for the critical load position for longitudinal cracking condition and for transverse cracking condition with positive temperature differential as well as negative temperature differential. The slab sizes considered in the analysis are 1.0 m × 1.0 m, 1.25 m × 1.25 m, 1.5 m × 1.5 m, 1.75 m × 1.75 m and 2.0 m × 2.0 m. Equations are given separately for single, tandem and tridem axles. The stresses for different slab sizes, with different thicknesses and modulus of subgrade reaction values (k) for different temperature differentials and axle loads can be calculated using the regression equations presented in the following paragraphs. The regression equations for different slab sizes are presented in **Tables A-I to A-V**. For each slab size, separate equations are available for different combinations of analysis with axle type (single, tandem, tridem), direction of crack (longitudinal or transverse) and temperature differential (positive or negative) and for three different ranges of modulus of subgrade reaction values. The longitudinal cracking analysis equations are same for both with and without concrete shoulder cases. Explanation for different notations used in the tables and in the regression equations, is given below.

SA	Single Axle
TA	Tandem Axle
TR	Tridem Axle
T	Transverse cracking
L	Longitudinal cracking
Δ P	Positive temperature differential
Δ N	Negative temperature differential
A	ΔT
B	Ph/kl^4
C	$\log_{10}(k)$
D	$\log_{10}(l)$

The inputs required for calculating the magnitude of stress for a particular load case and for a particular condition, are listed below along with the units to be used in the regression equations.

σ	Magnitude of stress in MPa
ΔT	Temperature differential magnitude in °C (without sign + / -)
P	Axle load in kN (Total Load of Single/Tandem/Tridem Axle)
h	Thickness of the slab in m
k	Modulus of subgrade reaction value in MPa/m
l	Radius of relative stiffness in m = $\sqrt[4]{\{(E.h^3)/[12k(1-\mu^2)]\}}$
E	Elastic modulus of concrete in MPa (30,000 MPa)
μ	Poisson's ratio of concrete (taken as 0.15)

Table A-I Critical Stress Calculation Equations for the Slab Size of 1.0 m × 1.0 m

Axle Type - direction of crack -Temperature differential	Range of k values in MPa/m	Equation for calculating the critical stress for the selected load case	Eq. No.	R^2	No. of Analysis points
Transverse cracking condition with positive temperature differential for slab with concrete shoulder			**Slab size: 1.0 m × 1.0 m**		
SA - T - ΔP	k <100	σ = 0.5858 + 0.0008 (A) + 1.4576 (B) + 0.0007 (A)(B) - 0.3796 (C) - 0.7987 (D)	I.1.1	0.9996	250
SA - T - ΔP	100 ≤ k < 150	σ = 0.7534 + 0.0013 (A) + 1.4145 (B) + 0.0012 (A)(B) - 0.4246 (C) - 0.7242 (D)	I.1.2	0.9997	250
SA - T - ΔP	k ≥ 150	σ = 0.9757 + 0.0023 (A) + 1.3525 (B) + 0.0019 (A)(B) - 0.4881 (C) - 0.7358 (D)	I.1.3	0.999	375
TA - T - ΔP	k <100	σ = 0.5636 + 0.0009 (A) + 0.7262 (B) + 0.0003 (A)(B) - 0.3703 (C) - 0.8252 (D)	I.1.4	0.9997	250
TA - T - ΔP	100 ≤ k < 150	σ = 0.7311 + 0.0014 (A) + 0.706 (B) + 0.0005 (A)(B) - 0.4176 (C) - 0.7564 (D)	I.1.5	0.9997	250
TA - T - ΔP	k ≥ 150	σ = 0.9373 + 0.0024 (A) + 0.6763 (B) + 0.0009 (A)(B) - 0.4765 (C) - 0.7763 (D)	I.1.6	0.9991	375
TR - T - ΔP	k <100	σ = 0.5636 + 0.0009 (A) + 0.4841 (B) + 0.0002 (A)(B) - 0.3703 (C) - 0.8252 (D)	I.1.7	0.9997	250
TR - T - ΔP	100 ≤ k < 150	σ = 0.7311 + 0.0014 (A) + 0.4707 (B) + 0.0004 (A)(B) - 0.4176 (C) - 0.7564 (D)	I.1.8	0.9997	250
TR - T - ΔP	k ≥ 150	σ = 0.9373 + 0.0024 (A) + 0.4509 (B) + 0.0006 (A)(B) - 0.4765 (C) - 0.7763 (D)	I.1.9	0.9991	375
Transverse cracking condition with negative temperature differential for slab with concrete shoulder			**Slab size: 1.0 m × 1.0 m**		
SA - T - ΔN	k <100	σ = 0.4789 - 0.0007 (A) + 0.7947 (B) - 0.0004 (A)(B) - 0.2884 (C) - 0.2704 (D)	I.2.1	0.9989	250
SA - T - ΔN	100 ≤ k < 150	σ = 0.5877 - 0.0005 (A) + 0.768 (B) - 0.0009 (A)(B) - 0.2819 (C) + 0.0663 (D)	I.2.2	0.9989	250
SA - T - ΔN	k ≥ 150	σ = 0.1007 + 0.0043 (A) + 0.736 (B) - 0.0028 (A)(B) + 0.0364 (C) + 0.7555 (D)	I.2.3	0.992	375
TA - T - ΔN	k <100	σ = -0.0062 + 0.0008 (A) + 0.4035 (B) + 0.0003 (A)(B) + 0.0469 (C) + 0.3713 (D)	I.2.4	0.9991	250
TA - T - ΔN	100 ≤ k < 150	σ = -0.0389 + 0.0014 (A) + 0.3931 (B) + 0.0005 (A)(B) + 0.0971 (C) + 0.5903 (D)	I.2.5	0.9984	250
TA - T - ΔN	k ≥ 150	σ = -0.135 + 0.0024 (A) + 0.3777 (B) + 0.0009 (A)(B) + 0.1911 (C) + 0.9092 (D)	I.2.6	0.9957	375
TR - T - ΔN	k <100	σ = -0.0062 + 0.0008 (A) + 0.269 (B) + 0.0002 (A)(B) + 0.0469 (C) + 0.3713 (D)	I.2.7	0.9991	250
TR - T - ΔN	100 ≤ k < 150	σ = -0.0389 + 0.0014 (A) + 0.2621 (B) + 0.0003 (A)(B) + 0.0971 (C) + 0.5903 (D)	I.2.8	0.9984	250
TR - T - ΔN	k ≥ 150	σ = -0.135 + 0.0024 (A) + 0.2518 (B) + 0.0006 (A)(B) + 0.1911 (C) + 0.9092 (D)	I.2.9	0.9957	375
Longitudinal cracking condition with positive temperature differential for slab with/without concrete shoulder			**Slab size: 1.0 m × 1.0 m**		
SA - L - ΔP	k <100	σ = 0.5951 + 0.0007 (A) + 0.9908 (B) + 0.0007 (A)(B) - 0.3947 (C) - 0.8965 (D)	I.3.1	0.9993	250
SA - L - ΔP	100 ≤ k < 150	σ = 0.7679 + 0.0011 (A) + 0.9507 (B) + 0.0011 (A)(B) - 0.4482 (C) - 0.8642 (D)	I.3.2	0.9995	250
SA - L - ΔP	k ≥ 150	σ = 0.9853 + 0.0022 (A) + 0.8939 (B) + 0.0018 (A)(B) - 0.5248 (C) - 0.981 (D)	I.3.3	0.9985	375
TA - L - ΔP	k <100	σ = 0.5917 + 0.0007 (A) + 0.4984 (B) + 0.0003 (A)(B) - 0.394 (C) - 0.9094 (D)	I.3.4	0.9993	250
TA - L - ΔP	100 ≤ k < 150	σ = 0.7664 + 0.0013 (A) + 0.4784 (B) + 0.0006 (A)(B) - 0.4497 (C) - 0.8847 (D)	I.3.5	0.9995	250
TA - L - ΔP	k ≥ 150	σ = 1.0034 + 0.0022 (A) + 0.4497 (B) + 0.0009 (A)(B) - 0.5336 (C) - 0.9919 (D)	I.3.6	0.9985	375
TR - L - ΔP	k <100	σ = 0.5917 + 0.0007 (A) + 0.3322 (B) + 0.0002 (A)(B) - 0.394 (C) - 0.9094 (D)	I.3.7	0.9993	250
TR - L - ΔP	100 ≤ k < 150	σ = 0.7664 + 0.0013 (A) + 0.3189 (B) + 0.0004 (A)(B) - 0.4497 (C) - 0.8847 (D)	I.3.8	0.9995	250
TR - L - ΔP	k ≥ 150	σ = 1.0034 + 0.0022 (A) + 0.2998 (B) + 0.0006 (A)(B) - 0.5336 (C) - 0.9919 (D)	I.3.9	0.9985	375

Longitudinal cracking condition with negative temperature differential for slab with/without concrete shoulder			**Slab size: 1.0 m × 1.0 m**		
SA - L - ΔN	k <100	σ = -0.1646 + 0.0006 (A) + 0.7876 (B) + 0.0006 (A)(B) + 0.1727 (C) + 0.8173 (D)	I.4.1	0.9987	250
SA - L - ΔN	100 ≤ k < 150	σ = -0.1943 + 0.0009 (A) + 0.7706 (B) + 0.001 (A)(B) + 0.2167 (C) + 1.0085 (D)	I.4.2	0.9979	250
SA - L - ΔN	k ≥ 150	σ = -0.2943 + 0.0016 (A) + 0.7466 (B) + 0.0015 (A)(B) + 0.3079 (C) + 1.3154 (D)	I.4.3	0.9952	375
TA - L - ΔN	k <100	σ = -0.242 + 0.0006 (A) + 0.3805 (B) + 0.0003 (A)(B) + 0.2191 (C) + 0.8745 (D)	I.4.4	0.9987	250
TA - L - ΔN	100 ≤ k < 150	σ = -0.3138 + 0.0009 (A) + 0.375 (B) + 0.0004 (A)(B) + 0.279 (C) + 1.0632 (D)	I.4.5	0.9978	250
TA - L - ΔN	k ≥ 150	σ = -0.4231 + 0.0016 (A) + 0.3658 (B) + 0.0007 (A)(B) + 0.3704 (C) + 1.3751 (D)	I.4.6	0.9952	375
TR - L - ΔN	k <100	σ = -0.242 + 0.0006 (A) + 0.2537 (B) + 0.0002 (A)(B) + 0.2191 (C) + 0.8745 (D)	I.4.7	0.9987	250
TR - L - ΔN	100 ≤ k < 150	σ = -0.3138 + 0.0009 (A) + 0.25 (B) + 0.0003 (A)(B) + 0.279 (C) + 1.0632 (D)	I.4.8	0.9978	250
TR - L - ΔN	k ≥ 150	σ = -0.4231 + 0.0016 (A) + 0.2439 (B) + 0.0005 (A)(B) + 0.3704 (C) + 1.3751 (D)	I.4.9	0.9952	375
Transverse cracking condition with positive temperature differential for slab without concrete shoulder			**Slab size: 1.0 m × 1.0 m**		
SA - T - ΔP	k <100	σ = 0.7232 + 0.0009 (A) + 1.5951 (B) + 0.0006 (A)(B) - 0.4767 (C) - 1.0308 (D)	I.5.1	0.9996	250
SA - T - ΔP	100 ≤ k < 150	σ = 0.9979 + 0.0015 (A) + 1.547 (B) + 0.0011 (A)(B) - 0.5795 (C) - 1.0513 (D)	I.5.2	0.9997	250
SA - T - ΔP	k ≥ 150	σ = 1.389 + 0.0024 (A) + 1.475 (B) + 0.0019 (A)(B) - 0.734 (C) - 1.2709 (D)	I.5.3	0.9992	375
TA - T - ΔP	k <100	σ = 0.6305 + 0.0008 (A) + 0.7776 (B) + 0.0003 (A)(B) - 0.4304 (C) - 1.0701 (D)	I.5.4	0.9997	250
TA - T - ΔP	100 ≤ k < 150	σ = 0.8585 + 0.0014 (A) + 0.7577 (B) + 0.0005 (A)(B) - 0.5192 (C) - 1.1084 (D)	I.5.5	0.9998	250
TA - T - ΔP	k ≥ 150	σ = 1.1928 + 0.0025 (A) + 0.7271 (B) + 0.0009 (A)(B) - 0.656 (C) - 1.3188 (D)	I.5.6	0.9993	375
TR - T - ΔP	k <100	σ = 0.6305 + 0.0008 (A) + 0.5184 (B) + 0.0002 (A)(B) - 0.4304 (C) - 1.0701 (D)	I.5.7	0.9997	250
TR - T - ΔP	100 ≤ k < 150	σ = 0.8585 + 0.0014 (A) + 0.5051 (B) + 0.0004 (A)(B) - 0.5192 (C) - 1.1084 (D)	I.5.8	0.9998	250
TR - T - ΔP	k ≥ 150	σ = 1.1928 + 0.0025 (A) + 0.4847 (B) + 0.0006 (A)(B) - 0.656 (C) - 1.3188 (D)	I.5.9	0.9993	375
Transverse cracking condition with negative temperature differential for slab without concrete shoulder			**Slab size: 1.0 m × 1.0 m**		
SA - T - ΔN	k <100	σ = -0.1532 + 0.0011 (A) + 0.7858 (B) + 0.0006 (A)(B) + 0.1759 (C) + 0.9024 (D)	I.6.1	0.9981	250
SA - T - ΔN	100 ≤ k < 150	σ = -0.2007 + 0.0018 (A) + 0.7678 (B) + 0.0008 (A)(B) + 0.226 (C) + 1.0621 (D)	I.6.2	0.9972	250
SA - T - ΔN	k ≥ 150	σ = -0.3641 + 0.0027 (A) + 0.7437 (B) + 0.0015 (A)(B) + 0.3436 (C) + 1.3546 (D)	I.6.3	0.9944	375
TA - T - ΔN	k <100	σ = -0.1557 + 0.0008 (A) + 0.4294 (B) + 0.0003 (A)(B) + 0.1302 (C) + 0.4038 (D)	I.6.4	0.9995	250
TA - T - ΔN	100 ≤ k < 150	σ = -0.1952 + 0.0013 (A) + 0.4243 (B) + 0.0005 (A)(B) + 0.171 (C) + 0.5896 (D)	I.6.5	0.999	250
TA - T - ΔN	k ≥ 150	σ = -0.2468 + 0.0022 (A) + 0.4137 (B) + 0.0009 (A)(B) + 0.2365 (C) + 0.8977 (D)	I.6.6	0.9972	375
TR - T - ΔN	k <100	σ = -0.1557 + 0.0008 (A) + 0.2863 (B) + 0.0002 (A)(B) + 0.1302 (C) + 0.4038 (D)	I.6.7	0.9995	250
TR - T - ΔN	100 ≤ k < 150	σ = -0.1952 + 0.0013 (A) + 0.2829 (B) + 0.0003 (A)(B) + 0.171 (C) + 0.5896 (D)	I.6.8	0.999	250
TR - T - ΔN	k ≥ 150	σ = -0.2468 + 0.0022 (A) + 0.2758 (B) + 0.0006 (A)(B) + 0.2365 (C) + 0.8977 (D)	I.6.9	0.9972	375

SA = Single Axle; TA= Tandem Axle; TR= Tridem Axle; T = Transverse cracking; L= Longitudinal cracking; ΔP= Positive temperature differential; ΔN= Negative temperature differential; A= ΔT; B= Ph/kl^4 ; C= $\log_{10}(k)$; D= $\log_{10}(l)$; k= Effective Modulus of subgrade reaction, MPa/m

Table A-II Critical Stress Calculation Equations for the Slab Size of 1.25 m × 1.25 m

Axle Type - direction of crack -Temperature differential	Range of k values in MPa/m	Equation for calculating the critical stress for the selected load case	Eq. No.	R^2	No. of Analysis points
Transverse cracking condition with positive temperature differential for slab with concrete shoulder			**Slab size: 1.25 m × 1.25 m**		
SA - T - ΔP	k <100	σ = 0.7558 + 0.0019 (A) + 1.6561 (B) + 0.0015 (A)(B) - 0.4347 (C) - 0.5578 (D)	II.1.1	0.9992	250
SA - T - ΔP	100 ≤ k < 150	σ = 0.9245 + 0.0032 (A) + 1.5809 (B) + 0.0024 (A)(B) - 0.4537 (C) - 0.4191 (D)	II.1.2	0.999	250
SA - T - ΔP	k ≥ 150	σ = 1.101 + 0.0056 (A) + 1.4791 (B) + 0.0039 (A)(B) - 0.4713 (C) - 0.374 (D)	II.1.3	0.9972	375
TA - T - ΔP	k <100	σ = 0.5617 + 0.0019 (A) + 0.7703 (B) + 0.0008 (A)(B) - 0.3466 (C) - 0.721 (D)	II.1.4	0.9994	250
TA - T - ΔP	100 ≤ k < 150	σ = 0.6662 + 0.0032 (A) + 0.7418 (B) + 0.0012 (A)(B) - 0.3561 (C) - 0.6429 (D)	II.1.5	0.9993	250
TA - T - ΔP	k ≥ 150	σ = 0.7444 + 0.0056 (A) + 0.7015 (B) + 0.002 (A)(B) - 0.3476 (C) - 0.6099 (D)	II.1.6	0.9977	375
TR - T - ΔP	k <100	σ = 0.5617 + 0.0019 (A) + 0.5135 (B) + 0.0005 (A)(B) - 0.3466 (C) - 0.721 (D)	II.1.7	0.9994	250
TR - T - ΔP	100 ≤ k < 150	σ = 0.6662 + 0.0032 (A) + 0.4945 (B) + 0.0008 (A)(B) - 0.3561 (C) - 0.6429 (D)	II.1.8	0.9993	250
TR - T - ΔP	k ≥ 150	σ = 0.7444 + 0.0056 (A) + 0.4677 (B) + 0.0013 (A)(B) - 0.3476 (C) - 0.6099 (D)	II.1.9	0.9977	375
Transverse cracking condition with negative temperature differential for slab with concrete shoulder			**Slab size: 1.25 m × 1.25 m**		
SA - T - ΔN	k <100	σ = -0.2163 + 0.004 (A) + 0.8492 (B) - 0.0011 (A)(B) + 0.1943 (C) + 0.8675 (D)	II.2.1	0.9962	250
SA - T - ΔN	100 ≤ k < 150	σ = -0.4076 + 0.0051 (A) + 0.8044 (B) + 0.0003 (A)(B) + 0.358 (C) + 1.3322 (D)	II.2.2	0.9946	250
SA - T - ΔN	k ≥ 150	σ = -0.6887 + 0.006 (A) + 0.754 (B) + 0.0027 (A)(B) + 0.5552 (C) + 1.794 (D)	II.2.3	0.9869	375
TA - T - ΔN	k <100	σ = 0.3249 + 0.0019 (A) + 0.6623 (B) + 0.0008 (A)(B) - 0.1105 (C) + 0.4646 (D)	II.2.4	0.9986	250
TA - T - ΔN	100 ≤ k < 150	σ = 0.4653 + 0.0033 (A) + 0.631 (B) + 0.0012 (A)(B) - 0.1186 (C) + 0.6668 (D)	II.2.5	0.998	250
TA - T - ΔN	k ≥ 150	σ = 0.6431 + 0.0058 (A) + 0.5862 (B) + 0.002 (A)(B) - 0.1247 (C) + 0.8786 (D)	II.2.6	0.9944	375
TR - T - ΔN	k <100	σ = 0.3249 + 0.0019 (A) + 0.4415 (B) + 0.0005 (A)(B) - 0.1105 (C) + 0.4646 (D)	II.2.7	0.9986	250
TR - T - ΔN	100 ≤ k < 150	σ = 0.4653 + 0.0033 (A) + 0.4207 (B) + 0.0008 (A)(B) - 0.1186 (C) + 0.6668 (D)	II.2.8	0.998	250
TR - T - ΔN	k ≥ 150	σ = 0.6431 + 0.0058 (A) + 0.3908 (B) + 0.0013 (A)(B) - 0.1247 (C) + 0.8786 (D)	II.2.9	0.9944	375
Longitudinal cracking condition with positive temperature differential for slab with/without concrete shoulder			**Slab size: 1.25 m × 1.25 m**		
SA - L - ΔP	k <100	σ = 0.5863 + 0.0019 (A) + 1.2231 (B) + 0.0015 (A)(B) - 0.3247 (C) - 0.3145 (D)	II.3.1	0.999	250
SA - L - ΔP	100 ≤ k < 150	σ = 0.7297 + 0.0031 (A) + 1.1565 (B) + 0.0024 (A)(B) - 0.3473 (C) - 0.2696 (D)	II.3.2	0.9989	250
SA - L - ΔP	k ≥ 150	σ = 0.9088 + 0.0052 (A) + 1.0659 (B) + 0.0039 (A)(B) - 0.3894 (C) - 0.3614 (D)	II.3.3	0.9965	375
TA - L - ΔP	k <100	σ = 0.7012 + 0.0019 (A) + 0.6349 (B) + 0.0007 (A)(B) - 0.3936 (C) - 0.3911 (D)	II.3.4	0.9989	250
TA - L - ΔP	100 ≤ k < 150	σ = 0.8716 + 0.0031 (A) + 0.5983 (B) + 0.0012 (A)(B) - 0.4227 (C) - 0.3351 (D)	II.3.5	0.9989	250
TA - L - ΔP	k ≥ 150	σ = 1.0924 + 0.0053 (A) + 0.5485 (B) + 0.0019 (A)(B) - 0.4754 (C) - 0.4185 (D)	II.3.6	0.9962	375
TR - L - ΔP	k <100	σ = 0.7012 + 0.0019 (A) + 0.4233 (B) + 0.0005 (A)(B) - 0.3936 (C) - 0.3911 (D)	II.3.7	0.9989	250
TR - L - ΔP	100 ≤ k < 150	σ = 0.8716 + 0.0031 (A) + 0.3989 (B) + 0.0008 (A)(B) - 0.4227 (C) - 0.3351 (D)	II.3.8	0.9989	250
TR - L - ΔP	k ≥ 150	σ = 1.0924 + 0.0053 (A) + 0.3657 (B) + 0.0013 (A)(B) - 0.4754 (C) - 0.4185 (D)	II.3.9	0.9962	375

Longitudinal cracking condition with negative temperature differential for slab with/without concrete shoulder			**Slab size: 1.25 m × 1.25 m**		
SA - L - ΔN	k <100	σ = 0.0986 + 0.0015 (A) + 0.9685 (B) + 0.0012 (A)(B) + 0.0441 (C) + 0.8577 (D)	II.4.1	0.9976	250
SA - L - ΔN	100 ≤ k < 150	σ = 0.1741 + 0.0024 (A) + 0.9203 (B) + 0.002 (A)(B) + 0.06 (C) + 1.0685 (D)	II.4.2	0.9966	250
SA - L - ΔN	k ≥ 150	σ = 0.1718 + 0.0042 (A) + 0.8576 (B) + 0.003 (A)(B) + 0.1184 (C) + 1.266 (D)	II.4.3	0.9925	375
TA - L - ΔN	k <100	σ = 0.1214 + 0.0013 (A) + 0.487 (B) + 0.0006 (A)(B) + 0.034 (C) + 0.8789 (D)	II.4.4	0.9977	250
TA - L - ΔN	100 ≤ k < 150	σ = 0.2055 + 0.0023 (A) + 0.4619 (B) + 0.001 (A)(B) + 0.0448 (C) + 1.0644 (D)	II.4.5	0.9967	250
TA - L - ΔN	k ≥ 150	σ = 0.1958 + 0.0041 (A) + 0.43 (B) + 0.0015 (A)(B) + 0.1056 (C) + 1.2439 (D)	II.4.6	0.9927	375
TR - L - ΔN	k <100	σ = 0.1214 + 0.0013 (A) + 0.3247 (B) + 0.0004 (A)(B) + 0.034 (C) + 0.8789 (D)	II.4.7	0.9977	250
TR - L - ΔN	100 ≤ k < 150	σ = 0.2055 + 0.0023 (A) + 0.3079 (B) + 0.0007 (A)(B) + 0.0448 (C) + 1.0644 (D)	II.4.8	0.9967	250
TR - L - ΔN	k ≥ 150	σ = 0.1958 + 0.0041 (A) + 0.2867 (B) + 0.001 (A)(B) + 0.1056 (C) + 1.2439 (D)	II.4.9	0.9927	375
Transverse cracking condition with positive temperature differential for slab without concrete shoulder			**Slab size: 1.25 m × 1.25 m**		
SA - T - ΔP	k <100	σ = 0.9906 + 0.0019 (A) + 1.8032 (B) + 0.0015 (A)(B) - 0.6 (C) - 0.9607 (D)	II.5.1	0.9993	250
SA - T - ΔP	100 ≤ k < 150	σ = 1.211 + 0.0032 (A) + 1.7215 (B) + 0.0024 (A)(B) - 0.6531 (C) - 0.9695 (D)	II.5.2	0.9994	250
SA - T - ΔP	k ≥ 150	σ = 1.5549 + 0.0056 (A) + 1.6113 (B) + 0.0039 (A)(B) - 0.7627 (C) - 1.1322 (D)	II.5.3	0.9981	375
TA - T - ΔP	k <100	σ = 0.6958 + 0.0019 (A) + 0.8226 (B) + 0.0008 (A)(B) - 0.4518 (C) - 1.0714 (D)	II.5.4	0.9996	250
TA - T - ΔP	100 ≤ k < 150	σ = 0.8169 + 0.0033 (A) + 0.7944 (B) + 0.0012 (A)(B) - 0.4822 (C) - 1.1146 (D)	II.5.5	0.9996	250
TA - T - ΔP	k ≥ 150	σ = 1.025 + 0.0056 (A) + 0.7534 (B) + 0.002 (A)(B) - 0.5536 (C) - 1.2774 (D)	II.5.6	0.9986	375
TR - T - ΔP	k <100	σ = 0.6958 + 0.0019 (A) + 0.5484 (B) + 0.0005 (A)(B) - 0.4518 (C) - 1.0714 (D)	II.5.7	0.9996	250
TR - T - ΔP	100 ≤ k < 150	σ = 0.8169 + 0.0033 (A) + 0.5296 (B) + 0.0008 (A)(B) - 0.4822 (C) - 1.1146 (D)	II.5.8	0.9996	250
TR - T - ΔP	k ≥ 150	σ = 1.025 + 0.0056 (A) + 0.5023 (B) + 0.0013 (A)(B) - 0.5536 (C) - 1.2774 (D)	II.5.9	0.9986	375
Transverse cracking condition with negative temperature differential for slab without concrete shoulder			**Slab size: 1.25 m × 1.25 m**		
SA - T - ΔN	k <100	σ = -0.1469 + 0.0018 (A) + 0.9832 (B) + 0.0015 (A)(B) + 0.2454 (C) + 1.5567 (D)	II.6.1	0.9955	250
SA - T - ΔN	100 ≤ k < 150	σ = -0.1254 + 0.0033 (A) + 0.935 (B) + 0.0022 (A)(B) + 0.2943 (C) + 1.8569 (D)	II.6.2	0.9933	250
SA - T - ΔN	k ≥ 150	σ = -0.3206 + 0.0062 (A) + 0.8816 (B) + 0.0029 (A)(B) + 0.435 (C) + 2.0967 (D)	II.6.3	0.9892	375
TA - T - ΔN	k <100	σ = 0.1504 + 0.002 (A) + 0.6553 (B) + 0.0008 (A)(B) - 0.0755 (C) - 0.1373 (D)	II.6.4	0.9997	250
TA - T - ΔN	100 ≤ k < 150	σ = 0.281 + 0.0032 (A) + 0.637 (B) + 0.0012 (A)(B) - 0.1211 (C) - 0.1283 (D)	II.6.5	0.9995	250
TA - T - ΔN	k ≥ 150	σ = 0.4904 + 0.0057 (A) + 0.6053 (B) + 0.002 (A)(B) - 0.185 (C) - 0.1106 (D)	II.6.6	0.998,	375
TR - T - ΔN	k <100	σ = 0.1504 + 0.002 (A) + 0.4368 (B) + 0.0005 (A)(B) - 0.0755 (C) - 0.1373 (D)	II.6.7	0.9997	250
TR - T - ΔN	100 ≤ k < 150	σ = 0.281 + 0.0032 (A) + 0.4247 (B) + 0.0008 (A)(B) - 0.1211 (C) - 0.1283 (D)	II.6.8	0.9995	250
TR - T - ΔN	k ≥ 150	σ = 0.4904 + 0.0057 (A) + 0.4035 (B) + 0.0013 (A)(B) - 0.185 (C) - 0.1106 (D)	II.6.9	0.998	375

SA = Single Axle; TA= Tandem Axle; TR= Tridem Axle; T = Transverse cracking; L= Longitudinal cracking; ΔP= Positive temperature differential; ΔN= Negative temperature differential; A= ΔT; B= Ph/kl⁴ ; C= $\log_{10}(k)$; D= $\log_{10}(l)$; k= Effective Modulus of subgrade reaction, MPa/m

Table A-III Critical Stress Calculation Equations for the Slab Size of 1.5 m × 1.5 m

Axle Type - direction of crack -Temperature differential	Range of k values in MPa/m	Equation for calculating the critical stress for the selected load case	Eq. No.	R^2	No. of Analysis points
Transverse cracking condition with positive temperature differential for slab with concrete shoulder			**Slab size: 1.5 m × 1.5 m**		
SA - T - ΔP	k <100	σ = 0.9017 + 0.0038 (A) + 1.7914 (B) + 0.0028 (A)(B) - 0.453 (C) - 0.1334 (D)	III.1.1	0.9979	250
SA - T - ΔP	100 ≤ k < 150	σ = 1.0666 + 0.0064 (A) + 1.6743 (B) + 0.0045 (A)(B) - 0.4458 (C) + 0.0103 (D)	III.1.2	0.9975	250
SA - T - ΔP	k ≥ 150	σ = 1.1529 + 0.0111 (A) + 1.5278 (B) + 0.0068 (A)(B) - 0.4125 (C) - 0.0092 (D)	III.1.3	0.9935	375
TA - T - ΔP	k <100	σ = 0.5497 + 0.0038 (A) + 0.8037 (B) + 0.0014 (A)(B) - 0.2935 (C) - 0.4544 (D)	III.1.4	0.9986	250
TA - T - ΔP	100 ≤ k < 150	σ = 0.586 + 0.0064 (A) + 0.7621 (B) + 0.0022 (A)(B) - 0.2595 (C) - 0.371 (D)	III.1.5	0.9981	250
TA - T - ΔP	k ≥ 150	σ = 0.5607 + 0.0112 (A) + 0.7071 (B) + 0.0034 (A)(B) - 0.2038 (C) - 0.3718 (D)	III.1.6	0.9945	375
TR - T - ΔP	k <100	σ = 0.5497 + 0.0038 (A) + 0.5358 (B) + 0.001 (A)(B) - 0.2935 (C) - 0.4544 (D)	III.1.7	0.9986	250
TR - T - ΔP	100 ≤ k < 150	σ = 0.586 + 0.0064 (A) + 0.5081 (B) + 0.0015 (A)(B) - 0.2595 (C) - 0.371 (D)	III.1.8	0.9981	250
TR - T - ΔP	k ≥ 150	σ = 0.5607 + 0.0112 (A) + 0.4714 (B) + 0.0023 (A)(B) - 0.2038 (C) - 0.3718 (D)	III.1.9	0.9945	375
Transverse cracking condition with negative temperature differential for slab with concrete shoulder			**Slab size: 1.5 m × 1.5 m**		
SA - T - ΔN	k <100	σ = -0.2281 + 0.003 (A) + 0.9318 (B) + 0.0024 (A)(B) + 0.3505 (C) + 2.092 (D)	III.2.1	0.9909	250
SA - T - ΔN	100 ≤ k < 150	σ = -0.5084 + 0.0053 (A) + 0.87 (B) + 0.0038 (A)(B) + 0.5449 (C) + 2.3087 (D)	III.2.2	0.9887	250
SA - T - ΔN	k ≥ 150	σ = -0.7857 + 0.0096 (A) + 0.8014 (B) + 0.0057 (A)(B) + 0.7096 (C) + 2.4655 (D)	III.2.3	0.9773	375
TA - T - ΔN	k <100	σ = -0.3292 + 0.0039 (A) + 0.7756 (B) + 0.0014 (A)(B) + 0.379 (C) + 1.736 (D)	III.2.4	0.996	250
TA - T - ΔN	100 ≤ k < 150	σ = -0.4987 + 0.0066 (A) + 0.7424 (B) + 0.0022 (A)(B) + 0.5705 (C) + 2.4948 (D)	III.2.5	0.9931	250
TA - T - ΔN	k ≥ 150	σ = -0.5807 + 0.0115 (A) + 0.6908 (B) + 0.0034 (A)(B) + 0.7697 (C) + 3.5637 (D)	III.2.6	0.981	375
TR - T - ΔN	k <100	σ = -0.3314 + 0.004 (A) + 0.5115 (B) + 0.0009 (A)(B) + 0.3872 (C) + 1.8102 (D)	III.2.7	0.9958	250
TR - T - ΔN	100 ≤ k < 150	σ = -0.5818 + 0.0066 (A) + 0.4893 (B) + 0.0015 (A)(B) + 0.6229 (C) + 2.606 (D)	III.2.8	0.9926	250
TR - T - ΔN	k ≥ 150	σ = -0.6062 + 0.0113 (A) + 0.455 (B) + 0.0023 (A)(B) + 0.7921 (C) + 3.6504 (D)	III.2.9	0.9805	375
Longitudinal cracking condition with positive temperature differential for slab with/without concrete shoulder			**Slab size: 1.5 m × 1.5 m**		
SA - L - ΔP	k <100	σ = 0.5304 + 0.0035 (A) + 1.331 (B) + 0.0029 (A)(B) - 0.2363 (C) + 0.0826 (D)	III.3.1	0.998	250
SA - L - ΔP	100 ≤ k < 150	σ = 0.6275 + 0.006 (A) + 1.2393 (B) + 0.0045 (A)(B) - 0.2325 (C) + 0.0749 (D)	III.3.2	0.9974	250
SA - L - ΔP	k ≥ 150	σ = 0.6871 + 0.0107 (A) + 1.1211 (B) + 0.0067 (A)(B) - 0.2261 (C) - 0.0925 (D)	III.3.3	0.9923	375
TA - L - ΔP	k <100	σ = 0.7386 + 0.0037 (A) + 0.7592 (B) + 0.0014 (A)(B) - 0.2972 (C) + 0.6216 (D)	III.3.4	0.9968	250
TA - L - ΔP	100 ≤ k < 150	σ = 0.8973 + 0.0061 (A) + 0.6986 (B) + 0.0022 (A)(B) - 0.2772 (C) + 0.8194 (D)	III.3.5	0.996	250
TA - L - ΔP	k ≥ 150	σ = 1.0415 + 0.0107 (A) + 0.6224 (B) + 0.0034 (A)(B) - 0.2618 (C) + 0.8249 (D)	III.3.6	0.9919	250
TR - L - ΔP	k <100	σ = 0.7209 + 0.0037 (A) + 0.5073 (B) + 0.0009 (A)(B) - 0.3025 (C) + 0.4686 (D)	III.3.7	0.9971	250
TR - L - ΔP	100 ≤ k < 150	σ = 0.9042 + 0.0062 (A) + 0.468 (B) + 0.0015 (A)(B) - 0.2983 (C) + 0.6623 (D)	III.3.8	0.9964	250
TR - L - ΔP	k ≥ 150	σ = 1.0667 + 0.0107 (A) + 0.4178 (B) + 0.0023 (A)(B) - 0.2908 (C) + 0.6833 (D)	III.3.9	0.9901	375

Longitudinal cracking condition with negative temperature differential for slab with/without concrete shoulder			**Slab size: 1.5 m × 1.5 m**		
SA - L - ΔN	k <100	σ = 0.5719 + 0.0041 (A) + 1.0307 (B) + 0.0028 (A)(B) - 0.2387 (C) + 0.3526 (D)	III.4.1	0.996	250
SA - L - ΔN	100 ≤ k < 150	σ = 0.7755 + 0.0066 (A) + 0.9344 (B) + 0.0045 (A)(B) - 0.2777 (C) + 0.3684 (D)	III.4.2	0.9945	250
SA - L - ΔN	k ≥ 150	σ = 0.9679 + 0.0113 (A) + 0.8099 (B) + 0.0068 (A)(B) - 0.3179 (C) + 0.2219 (D)	III.4.3	0.9859	375
TA - L - ΔN	k <100	σ = 1.0354 + 0.004 (A) + 0.6677 (B) + 0.0014 (A)(B) - 0.3871 (C) + 1.4088 (D)	III.4.4	0.9919	250
TA - L - ΔN	100 ≤ k < 150	σ = 1.3821 + 0.0067 (A) + 0.5911 (B) + 0.0022 (A)(B) - 0.4225 (C) + 1.6572 (D)	III.4.5	0.9902	250
TA - L - ΔN	k ≥ 150	σ = 1.704 + 0.0114 (A) + 0.4987 (B) + 0.0034 (A)(B) - 0.4597 (C) + 1.6134 (D)	III.4.6	0.9779	375
TR - L - ΔN	k <100	σ = 1.0948 + 0.0038 (A) + 0.4559 (B) + 0.001 (A)(B) - 0.4336 (C) + 1.2613 (D)	III.4.7	0.993	250
TR - L - ΔN	100 ≤ k < 150	σ = 1.488 + 0.0065 (A) + 0.4043 (B) + 0.0015 (A)(B) - 0.497 (C) + 1.4431 (D)	III.4.8	0.9912	250
TR - L - ΔN	k ≥ 150	σ = 1.8576 + 0.0113 (A) + 0.3411 (B) + 0.0023 (A)(B) - 0.5508 (C) + 1.4116 (D)	III.4.9	0.9795	375
Transverse cracking condition with positive temperature differential for slab without concrete shoulder			**Slab size: 1.5 m × 1.5 m**		
SA - T - ΔP	k <100	σ = 1.1656 + 0.0038 (A) + 1.9519 (B) + 0.0029 (A)(B) - 0.661 (C) - 0.8231 (D)	III.5.1	0.9987	250
SA - T - ΔP	100 ≤ k < 150	σ = 1.4612 + 0.0064 (A) + 1.8305 (B) + 0.0045 (A)(B) - 0.7314 (C) - 0.8447 (D)	III.5.2	0.9985	250
SA - T - ΔP	k ≥ 150	σ = 1.7082 + 0.0111 (A) + 1.6754 (B) + 0.0068 (A)(B) - 0.7862 (C) - 1.0714 (D)	III.5.3	0.9959	375
TA - T - ΔP	k <100	σ = 0.6966 + 0.0038 (A) + 0.8587 (B) + 0.0014 (A)(B) - 0.4231 (C) - 0.9803 (D)	III.5.4	0.9991	250
TA - T - ΔP	100 ≤ k < 150	σ = 0.8047 + 0.0064 (A) + 0.8179 (B) + 0.0022 (A)(B) - 0.4407 (C) - 1.0468 (D)	III.5.5	0.9989	250
TA - T - ΔP	k ≥ 150	σ = 0.8833 + 0.0112 (A) + 0.7623 (B) + 0.0034 (A)(B) - 0.4531 (C) - 1.2445 (D)	III.5.6	0.9965	375
TR - T - ΔP	k <100	σ = 0.6966 + 0.0038 (A) + 0.5725 (B) + 0.0009 (A)(B) - 0.4231 (C) - 0.9803 (D)	III.5.7	0.9991	250
TR - T - ΔP	100 ≤ k < 150	σ = 0.8047 + 0.0064 (A) + 0.5453 (B) + 0.0015 (A)(B) - 0.4407 (C) - 1.0468 (D)	III.5.8	0.9989	250
TR - T - ΔP	k ≥ 150	σ = 0.8833 + 0.0112 (A) + 0.5082 (B) + 0.0023 (A)(B) - 0.4531 (C) - 1.2445 (D)	III.5.9	0.9965	375
Transverse cracking condition with negative temperature differential for slab without concrete shoulder			**Slab size: 1.5 m x 1.5 m**		
SA - T - ΔN	k <100	σ = 0.18 + 0.0034 (A) + 1.1902 (B) + 0.0023 (A)(B) + 0.1248 (C) + 2.0352 (D)	III.6.1	0.9927	250
SA - T - ΔN	100 ≤ k < 150	σ = 0.1982 + 0.0055 (A) + 1.0942 (B) + 0.0037 (A)(B) + 0.214 (C) + 2.3753 (D)	III.6.2	0.9907	250
SA - T - ΔN	k ≥ 150	σ = 0.1618 + 0.0095 (A) + 0.9791 (B) + 0.0057 (A)(B) + 0.3181 (C) + 2.6111 (D)	III.6.3	0.9808	375
TA - T - ΔN	k <100	σ = -0.8392 + 0.004 (A) + 0.7267 (B) + 0.0014 (A)(B) + 0.5464 (C) + 0.6092 (D)	III.6.4	0.9989	250
TA - T - ΔN	100 ≤ k < 150	σ = -1.0445 + 0.0065 (A) + 0.7233 (B) + 0.0022 (A)(B) + 0.6773 (C) + 1.1264 (D)	III.6.5	0.9975	250
TA - T - ΔN	k ≥ 150	σ = -1.1096 + 0.0113 (A) + 0.6998 (B) + 0.0034 (A)(B) + 0.8063 (C) + 2.0525 (D)	III.6.6	0.9912	375
TR - T - ΔN	k <100	σ = -0.7533 + 0.004 (A) + 0.4852 (B) + 0.0009 (A)(B) + 0.5191 (C) + 0.8102 (D)	III.6.7	0.9986	250
TR - T - ΔN	100 ≤ k < 150	σ = -0.9831 + 0.0066 (A) + 0.4801 (B) + 0.0015 (A)(B) + 0.6703 (C) + 1.3327 (D)	III.6.8	0.9971	250
TR - T - ΔN	k ≥ 150	σ = -1.0893 + 0.0114 (A) + 0.4628 (B) + 0.0023 (A)(B) + 0.8179 (C) + 2.2176 (D)	III.6.9	0.9906	375

SA = Single Axle; TA= Tandem Axle; TR= Tridem Axle; T = Transverse cracking; L= Longitudinal cracking; ΔP= Positive temperature differential; ΔN= Negative temperature differential; A= ΔT; B= Ph/kl⁴ ; C= $log_{10}(k)$; D= $log_{10}(l)$; k= Effective Modulus of subgrade reaction, MPa/m

Table A-IV Critical Stress Calculation Equations for the Slab Size of 1.75 m × 1.75 m

Axle Type - direction of crack -Temperature differential	Range of k values in MPa/m	Equation for calculating the critical stress for the selected load case	Eq. No.	R^2	No. of Analysis points
Transverse cracking condition with positive temperature differential for slab with concrete shoulder			**Slab size: 1.75 m × 1.75 m**		
SA - T - ΔP	k <100	σ = 0.842 + 0.0057 (A) + 1.924 (B) + 0.0039 (A)(B) - 0.4383 (C) - 0.4445 (D)	IV.1.1	0.9976	250
SA - T - ΔP	100 ≤ k < 150	σ = 0.9144 + 0.0096 (A) + 1.789 (B) + 0.006 (A)(B) - 0.4173 (C) - 0.4829 (D)	IV.1.2	0.9972	250
SA - T - ΔP	k ≥ 150	σ = 0.8591 + 0.0164 (A) + 1.623 (B) + 0.0089 (A)(B) - 0.3614 (C) - 0.7142 (D)	IV.1.3	0.9921	375
TA - T - ΔP	k <100	σ = 0.4652 + 0.0059 (A) + 0.8401 (B) + 0.0019 (A)(B) - 0.2545 (C) - 0.6949 (D)	IV.1.4	0.9981	250
TA - T - ΔP	100 ≤ k < 150	σ = 0.3542 + 0.0097 (A) + 0.7939 (B) + 0.003 (A)(B) - 0.1759 (C) - 0.758 (D)	IV.1.5	0.9974	250
TA - T - ΔP	k ≥ 150	σ = 0.2303 + 0.0162 (A) + 0.7345 (B) + 0.0045 (A)(B) - 0.112 (C) - 0.906 (D)	IV.1.6	0.9927	375
TR - T - ΔP	k <100	σ = 0.5885 + 0.0058 (A) + 0.584 (B) + 0.0013 (A)(B) - 0.3122 (C) - 0.5749 (D)	IV.1.7	0.9979	250
TR - T - ΔP	100 ≤ k < 150	σ = 0.5421 + 0.0095 (A) + 0.548 (B) + 0.002 (A)(B) - 0.2507 (C) - 0.6012 (D)	IV.1.8	0.9973	250
TR - T - ΔP	k ≥ 150	σ = 0.4354 + 0.0162 (A) + 0.5025 (B) + 0.003 (A)(B) - 0.1841 (C) - 0.7621 (D)	IV.1.9	0.9923	375
Transverse cracking condition with negative temperature differential for slab with concrete shoulder			**Slab size: 1.75 m × 1.75 m**		
SA - T - ΔN	k <100	σ = -0.2187 + 0.0047 (A) + 1.1298 (B) + 0.0033 (A)(B) + 0.2818 (C) + 1.7629 (D)	IV.2.1	0.9921	250
SA - T - ΔN	100 ≤ k < 150	σ = -0.4355 + 0.0076 (A) + 1.0464 (B) + 0.0052 (A)(B) + 0.4364 (C) + 1.922 (D)	IV.2.2	0.9895	250
SA - T - ΔN	k ≥ 150	σ = -0.5189 + 0.0132 (A) + 0.9361 (B) + 0.0077 (A)(B) + 0.5117 (C) + 1.9833 (D)	IV.2.3	0.9773	375
TA - T - ΔN	k <100	σ = -0.2679 + 0.0053 (A) + 0.6028 (B) + 0.0018 (A)(B) + 0.2185 (C) + 0.4957 (D)	IV.2.4	0.9975	250
TA - T - ΔN	100 ≤ k < 150	σ = -0.9263 + 0.0088 (A) + 0.5891 (B) + 0.0027 (A)(B) + 0.529 (C) + 0.3931 (D)	IV.2.5	0.9966	250
TA - T - ΔN	k ≥ 150	σ = -1.1144 + 0.0151 (A) + 0.5686 (B) + 0.004 (A)(B) + 0.6373 (C) + 0.8331 (D)	IV.2.6	0.9898	375
TR - T - ΔN	k <100	σ = -0.4119 + 0.0053 (A) + 0.4168 (B) + 0.0012 (A)(B) + 0.2915 (C) + 0.4379 (D)	IV.2.7	0.9976	250
TR - T - ΔN	100 ≤ k < 150	σ = -0.7752 + 0.009 (A) + 0.4066 (B) + 0.0018 (A)(B) + 0.4802 (C) + 0.6398 (D)	IV.2.8	0.996	250
TR - T - ΔN	k ≥ 150	σ = -0.9436 + 0.0153 (A) + 0.3875 (B) + 0.0026 (A)(B) + 0.5878 (C) + 1.0504 (D)	IV.2.9	0.9889	375
Longitudinal cracking condition with positive temperature differential for slab with/without concrete shoulder			**Slab size: 1.75 m × 1.75 m**		
SA - L - ΔP	k <100	σ = 0.1437 + 0.0053 (A) + 1.4543 (B) + 0.0039 (A)(B) + 0.0119 (C) + 0.5971 (D)	IV.3.1	0.9969	250
SA - L - ΔP	100 ≤ k < 150	σ = 0.1634 + 0.0089 (A) + 1.3532 (B) + 0.006 (A)(B) + 0.0224 (C) + 0.4004 (D)	IV.3.2	0.9956	250
SA - L - ΔP	k ≥ 150	σ = 0.1176 + 0.0154 (A) + 1.226 (B) + 0.0087 (A)(B) + 0.0398 (C) + 0.0534 (D)	IV.3.3	0.989	375
TA - L - ΔP	k <100	σ = 0.2216 + 0.0052 (A) + 0.8111 (B) + 0.002 (A)(B) + 0.0016 (C) + 1.0129 (D)	IV.3.4	0.9963	250
TA - L - ΔP	100 ≤ k < 150	σ = 0.2755 + 0.0088 (A) + 0.7494 (B) + 0.0031 (A)(B) + 0.0238 (C) + 0.9691 (D)	IV.3.5	0.9949	250
TA - L - ΔP	k ≥ 150	σ = 0.3175 + 0.0155 (A) + 0.6706 (B) + 0.0045 (A)(B) + 0.0305 (C) + 0.7252 (D)	IV.3.6	0.9871	375
TR - L - ΔP	k <100	σ = 0.2288 + 0.0052 (A) + 0.5414 (B) + 0.0013 (A)(B) - 0.0032 (C) + 0.9949 (D)	IV.3.7	0.9963	250
TR - L - ΔP	100 ≤ k < 150	σ = 0.2735 + 0.0087 (A) + 0.5004 (B) + 0.0021 (A)(B) + 0.0242 (C) + 0.9619 (D)	IV.3.8	0.995	250
TR - L - ΔP	k ≥ 150	σ = 0.304 + 0.0152 (A) + 0.4489 (B) + 0.003 (A)(B) + 0.04 (C) + 0.7767 (D)	IV.3.9	0.9876	375

Longitudinal cracking condition with negative temperature differential for slab with/without concrete shoulder			**Slab size: 1.75 m × 1.75 m**		
SA - L - ΔN	k <100	σ = 0.1674 + 0.0059 (A) + 1.2728 (B) + 0.0039 (A)(B) - 0.0147 (C) + 0.4729 (D)	IV.4.1	0.9961	250
SA - L - ΔN	100 ≤ k < 150	σ = 0.152 + 0.0096 (A) + 1.179 (B) + 0.0061 (A)(B) + 0.0363 (C) + 0.5721 (D)	IV.4.2	0.9943	250
SA - L - ΔN	k ≥ 150	σ = 0.2206 + 0.0162 (A) + 1.0502 (B) + 0.0091 (A)(B) + 0.0474 (C) + 0.6164 (D)	IV.4.3	0.9847	375
TA - L - ΔN	k <100	σ = 0.4282 + 0.006 (A) + 0.8077 (B) + 0.0019 (A)(B) - 0.081 (C) + 1.4809 (D)	IV.4.4	0.9935	250
TA - L - ΔN	100 ≤ k < 150	σ = 0.5411 + 0.0097 (A) + 0.7319 (B) + 0.0031 (A)(B) - 0.0333 (C) + 1.8077 (D)	IV.4.5	0.9913	250
TA - L - ΔN	k ≥ 150	σ = 0.6176 + 0.018 (A) + 0.6369 (B) + 0.0042 (A)(B) + 0.0451 (C) + 2.1795 (D)	IV.4.6	0.979	375
TR - L - ΔN	k <100	σ = 0.4831 + 0.0058 (A) + 0.5425 (B) + 0.0013 (A)(B) - 0.1081 (C) + 1.5056 (D)	IV.4.7	0.9933	250
TR - L - ΔN	100 ≤ k < 150	σ = 0.5976 + 0.0097 (A) + 0.491 (B) + 0.002 (A)(B) - 0.0596 (C) + 1.817 (D)	IV.4.8	0.9913	250
TR - L - ΔN	k ≥ 150	σ = 0.6802 + 0.0165 (A) + 0.427 (B) + 0.003 (A)(B) + 0.0038 (C) + 2.0466 (D)	IV.4.9	0.979	375
Transverse cracking condition with positive temperature differential for slab without concrete shoulder			**Slab size: 1.75 m × 1.75 m**		
SA - T - ΔP	k <100	σ = 1.1128 + 0.0058 (A) + 2.0874 (B) + 0.0039 (A)(B) - 0.6364 (C) - 1.1146 (D)	IV.5.1	0.9983	250
SA - T - ΔP	100 ≤ k < 150	σ = 1.3887 + 0.0096 (A) + 1.9425 (B) + 0.006 (A)(B) - 0.7197 (C) - 1.2777 (D)	IV.5.2	0.9981	250
SA - T - ΔP	k ≥ 150	σ = 1.4291 + 0.0162 (A) + 1.7645 (B) + 0.0089 (A)(B) - 0.7152 (C) - 1.695 (D)	IV.5.3	0.9946	375
TA - T - ΔP	k <100	σ = 0.6165 + 0.0057 (A) + 0.8911 (B) + 0.002 (A)(B) - 0.3695 (C) - 1.1536 (D)	IV.5.4	0.9986	250
TA - T - ΔP	100 ≤ k < 150	σ = 0.6162 + 0.0095 (A) + 0.8443 (B) + 0.0031 (A)(B) - 0.3545 (C) - 1.3326 (D)	IV.5.5	0.9981	250
TA - T - ΔP	k ≥ 150	σ = 0.5423 + 0.0162 (A) + 0.7838 (B) + 0.0045 (A)(B) - 0.3249 (C) - 1.6216 (D)	IV.5.6	0.9945	375
TR - T - ΔP	k <100	σ = 0.7224 + 0.0058 (A) + 0.6184 (B) + 0.0013 (A)(B) - 0.4313 (C) - 1.2053 (D)	IV.5.7	0.9986	250
TR - T - ΔP	100 ≤ k < 150	σ = 0.8037 + 0.0095 (A) + 0.5834 (B) + 0.002 (A)(B) - 0.4429 (C) - 1.3136 (D)	IV.5.8	0.9981	250
TR - T - ΔP	k ≥ 150	σ = 0.7796 + 0.0161 (A) + 0.5373 (B) + 0.003 (A)(B) - 0.4221 (C) - 1.5797 (D)	IV.5.9	0.9944	375
Transverse cracking condition with negative temperature differential for slab without concrete shoulder			**Slab size: 1.75 m × 1.75 m**		
SA - T - ΔN	k <100	σ = 0.1261 + 0.0048 (A) + 1.4013 (B) + 0.0033 (A)(B) + 0.0863 (C) + 1.6262 (D)	IV.6.1	0.9943	250
SA - T - ΔN	100 ≤ k < 150	σ = 0.1092 + 0.0078 (A) + 1.2884 (B) + 0.0052 (A)(B) + 0.1607 (C) + 1.753 (D)	IV.6.2	0.9927	250
SA - T - ΔN	k ≥ 150	σ = 0.1242 + 0.0133 (A) + 1.1516 (B) + 0.0076 (A)(B) + 0.2064 (C) + 1.7688 (D)	IV.6.3	0.984	375
TA - T - ΔN	k <100	σ = 0.6093 + 0.0056 (A) + 0.7605 (B) + 0.0019 (A)(B) - 0.2231 (C) + 0.9021 (D)	IV.6.4	0.9949	250
TA - T - ΔN	100 ≤ k < 150	σ = 0.7825 + 0.0093 (A) + 0.6885 (B) + 0.0029 (A)(B) - 0.2247 (C) + 1.033 (D)	IV.6.5	0.9938	250
TA - T - ΔN	k ≥ 150	σ = 0.7351 + 0.0159 (A) + 0.6075 (B) + 0.004 (A)(B) - 0.1606 (C) + 0.8103 (D)	IV.6.6	0.9885	375
TR - T - ΔN	k <100	σ = 0.6415 + 0.0056 (A) + 0.5075 (B) + 0.0013 (A)(B) - 0.2441 (C) + 0.8497 (D)	IV.6.7	0.995	250
TR - T - ΔN	100 ≤ k < 150	σ = 0.8066 + 0.0093 (A) + 0.4592 (B) + 0.002 (A)(B) - 0.2418 (C) + 0.9699 (D)	IV.6.8	0.9939	250
TR - T - ΔN	k ≥ 150	σ = 0.4728 + 0.0155 (A) + 0.407 (B) + 0.0028 (A)(B) - 0.046 (C) + 0.8109 (D)	IV.6.9	0.9889	375

SA = Single Axle; TA= Tandem Axle; TR= Tridem Axle; T = Transverse cracking; L= Longitudinal cracking; ΔP= Positive temperature differential; ΔN= Negative temperature differential; A= ΔT; B= Ph/kl^4 ; C= $\log_{10}(k)$; D= $\log_{10}(l)$; k= Effective Modulus of subgrade reaction, MPa/m

Table A-V Critical Stress Calculation Equations for the Slab Size of 2.0 m × 2.0 m

Axle Type - direction of crack -Temperature differential	Range of k values in MPa/m	Equation for calculating the critical stress for the selected load case	Eq. No.	R^2	No. of Analysis points
Transverse cracking condition with positive temperature differential for slab with concrete shoulder			**Slab size: 2.0 m × 2.0 m**		
SA - T - ΔP	k <100	σ = 0.8876 + 0.0095 (A) + 2.0456 (B) + 0.006 (A)(B) - 0.3916 (C) + 0.1938 (D)	V.1.1	0.9952	250
SA - T - ΔP	100 ≤ k < 150	σ = 0.9162 + 0.0157 (A) + 1.8577 (B) + 0.0088 (A)(B) - 0.3351 (C) + 0.086 (D)	V.1.2	0.9944	250
SA - T - ΔP	k ≥ 150	σ = 0.8078 + 0.0262 (A) + 1.6511 (B) + 0.012 (A)(B) - 0.2607 (C) - 0.2697 (D)	V.1.3	0.9876	375
TA - T - ΔP	k <100	σ = 0.3339 + 0.0095 (A) + 0.8664 (B) + 0.003 (A)(B) - 0.1313 (C) - 0.3241 (D)	V.1.4	0.9962	250
TA - T - ΔP	100 ≤ k < 150	σ = 0.2283 + 0.0156 (A) + 0.8042 (B) + 0.0044 (A)(B) - 0.0567 (C) - 0.4502 (D)	V.1.5	0.9948	250
TA - T - ΔP	k ≥ 150	σ = -0.0003 + 0.026 (A) + 0.7321 (B) + 0.0061 (A)(B) + 0.0409 (C) - 0.6934 (D)	V.1.6	0.9879	375
TR - T - ΔP	k <100	σ = 0.4029 + 0.0096 (A) + 0.5933 (B) + 0.002 (A)(B) - 0.1613 (C) - 0.2264 (D)	V.1.7	0.996	250
TR - T - ΔP	100 ≤ k < 150	σ = 0.3405 + 0.0158 (A) + 0.5488 (B) + 0.0029 (A)(B) - 0.0988 (C) - 0.3187 (D)	V.1.8	0.9946	250
TR - T - ΔP	k ≥ 150	σ = 0.1213 + 0.0262 (A) + 0.4971 (B) + 0.004 (A)(B) + 0.0016 (C) - 0.566 (D)	V.1.9	0.9876	375
Transverse cracking condition with negative temperature differential for slab with concrete shoulder			**Slab size: 2.0 m × 2.0 m**		
SA - T - ΔN	k <100	σ = -0.4064 + 0.0087 (A) + 1.0704 (B) + 0.0045 (A)(B) + 0.3375 (C) + 0.93 (D)	V.2.1	0.9933	250
SA - T - ΔN	100 ≤ k < 150	σ = -0.522 + 0.0146 (A) + 1.0033 (B) + 0.0063 (A)(B) + 0.413 (C) + 1.0651 (D)	V.2.2	0.9893	250
SA - T - ΔN	k ≥ 150	σ = -0.7777 + 0.0247 (A) + 0.9171 (B) + 0.008 (A)(B) + 0.5457 (C) + 1.218 (D)	V.2.3	0.9765	375
TA - T - ΔN	k <100	σ = -0.1145 + 0.0123 (A) + 0.6462 (B) - 0.0036 (A)(B) - 0.0059 (C) - 0.7646 (D)	V.2.4	0.9946	250
TA - T - ΔN	100 ≤ k < 150	σ = -0.7516 + 0.0226 (A) + 0.6113 (B) - 0.0027 (A)(B) + 0.2959 (C) - 0.83 (D)	V.2.5	0.9962	250
TA - T - ΔN	k ≥ 150	σ = -1.1201 + 0.0313 (A) + 0.5865 (B) - 0.0008 (A)(B) + 0.4496 (C) - 0.643 (D)	V.2.6	0.992	375
TR - T - ΔN	k <100	σ = -0.4667 + 0.0077 (A) + 0.3922 (B) + 0.0016 (A)(B) + 0.2984 (C) - 0.0234 (D)	V.2.7	0.9975	250
TR - T - ΔN	100 ≤ k < 150	σ = -0.6212 + 0.013 (A) + 0.3815 (B) + 0.0023 (A)(B) + 0.3554 (C) - 0.0558 (D)	V.2.8	0.9957	250
TR - T - ΔN	k ≥ 150	σ = -0.9451 + 0.0244 (A) + 0.3717 (B) + 0.0023 (A)(B) + 0.4715 (C) - 0.0494 (D)	V.2.9	0.9909	375
Longitudinal cracking condition with positive temperature differential for slab with/without concrete shoulder			**Slab size: 2.0 m × 2.0 m**		
SA - L - ΔP	k <100	σ = 0.0713 + 0.0098 (A) + 1.5204 (B) + 0.0049 (A)(B) + 0.0759 (C) + 0.7002 (D)	V.3.1	0.9946	250
SA - L - ΔP	100 ≤ k < 150	σ = 0.037 + 0.0156 (A) + 1.3897 (B) + 0.0078 (A)(B) + 0.106 (C) + 0.3822 (D)	V.3.2	0.9925	250
SA - L - ΔP	k ≥ 150	σ = -0.089 + 0.0277 (A) + 1.2424 (B) + 0.0104 (A)(B) + 0.1386 (C) - 0.0501 (D)	V.3.3	0.9835	375
TA - L - ΔP	k <100	σ = 0.0985 + 0.01 (A) + 0.8423 (B) + 0.0024 (A)(B) + 0.1024 (C) + 1.2822 (D)	V.3.4	0.9939	250
TA - L - ΔP	100 ≤ k < 150	σ = 0.1138 + 0.016 (A) + 0.7658 (B) + 0.0038 (A)(B) + 0.1382 (C) + 1.1344 (D)	V.3.5	0.9917	250
TA - L - ΔP	k ≥ 150	σ = 0.0483 + 0.026 (A) + 0.6769 (B) + 0.0054 (A)(B) + 0.1797 (C) + 0.8262 (D)	V.3.6	0.9816	375
TR - L - ΔP	k <100	σ = 0.1051 + 0.0098 (A) + 0.563 (B) + 0.0016 (A)(B) + 0.1019 (C) + 1.309 (D)	V.3.7	0.9939	250
TR - L - ΔP	100 ≤ k < 150	σ = 0.1241 + 0.0159 (A) + 0.5118 (B) + 0.0025 (A)(B) + 0.1359 (C) + 1.1613 (D)	V.3.8	0.9917	250
TR - L - ΔP	k ≥ 150	σ = 0.1748 + 0.0254 (A) + 0.4501 (B) + 0.0037 (A)(B) + 0.1276 (C) + 0.7989 (D)	V.3.9	0.9814	375

Longitudinal cracking condition with negative temperature differential for slab with/without concrete shoulder			Slab size: 2.0 m × 2.0 m		
SA - L - ΔN	k <100	σ = -0.2263 + 0.0096 (A) + 1.3965 (B) + 0.0057 (A)(B) + 0.2584 (C) + 1.0614 (D)	V.4.1	0.9939	250
SA - L - ΔN	100 ≤ k < 150	σ = -0.247 + 0.0159 (A) + 1.2916 (B) + 0.0083 (A)(B) + 0.315 (C) + 1.2947 (D)	V.4.2	0.9902	250
SA - L - ΔN	k ≥ 150	σ = -0.3499 + 0.0266 (A) + 1.1505 (B) + 0.0112 (A)(B) + 0.4148 (C) + 1.564 (D)	V.4.3	0.9765	375
TA - L - ΔN	k <100	σ = -0.1057 + 0.0096 (A) + 0.8473 (B) + 0.0029 (A)(B) + 0.2865 (C) + 2.3112 (D)	V.4.4	0.9908	250
TA - L - ΔN	100 ≤ k < 150	σ = -0.045 + 0.0159 (A) + 0.7697 (B) + 0.0042 (A)(B) + 0.3628 (C) + 2.8249 (D)	V.4.5	0.9863	250
TA - L - ΔN	k ≥ 150	σ = -0.1198 + 0.0283 (A) + 0.6816 (B) + 0.0048 (A)(B) + 0.4905 (C) + 3.2325 (D)	V.4.6	0.972	375
TR - L - ΔN	k <100	σ = -0.0638 + 0.0097 (A) + 0.5665 (B) + 0.0019 (A)(B) + 0.2576 (C) + 2.2253 (D)	V.4.7	0.991	250
TR - L - ΔN	100 ≤ k < 150	σ = -0.0053 + 0.0159 (A) + 0.5143 (B) + 0.0028 (A)(B) + 0.337 (C) + 2.7547 (D)	V.4.8	0.9866	250
TR - L - ΔN	k ≥ 150	σ = -0.0491 + 0.0271 (A) + 0.4503 (B) + 0.0036 (A)(B) + 0.465 (C) + 3.228 (D)	V.4.9	0.9705	375
Transverse cracking condition with positive temperature differential for slab without concrete shoulder			**Slab size: 2.0 m × 2.0 m**		
SA - T - ΔP	k <100	σ = 1.274 + 0.0096 (A) + 2.219 (B) + 0.006 (A)(B) - 0.6699 (C) - 0.7396 (D)	V.5.1	0.9965	250
SA - T - ΔP	100 ≤ k < 150	σ = 1.3982 + 0.0157 (A) + 2.0218 (B) + 0.0088 (A)(B) - 0.6581 (C) - 0.8968 (D)	V.5.2	0.9961	250
SA - T - ΔP	k ≥ 150	σ = 1.4132 + 0.0262 (A) + 1.8008 (B) + 0.0121 (A)(B) - 0.6334 (C) - 1.2857 (D)	V.5.3	0.9907	375
TA - T - ΔP	k <100	σ = 0.5142 + 0.0095 (A) + 0.9183 (B) + 0.003 (A)(B) - 0.2736 (C) - 0.9288 (D)	V.5.4	0.9971	250
TA - T - ΔP	100 ≤ k < 150	σ = 0.4668 + 0.0157 (A) + 0.8565 (B) + 0.0044 (A)(B) - 0.2342 (C) - 1.1223 (D)	V.5.5	0.9961	250
TA - T - ΔP	k ≥ 150	σ = 0.3198 + 0.0261 (A) + 0.7829 (B) + 0.006 (A)(B) - 0.1768 (C) - 1.4165 (D)	V.5.6	0.9904	375
TR - T - ΔP	k <100	σ = 0.5653 + 0.0095 (A) + 0.6273 (B) + 0.002 (A)(B) - 0.3022 (C) - 0.9389 (D)	V.5.7	0.9971	250
TR - T - ΔP	100 ≤ k < 150	σ = 0.5613 + 0.0156 (A) + 0.5839 (B) + 0.003 (A)(B) - 0.2751 (C) - 1.0786 (D)	V.5.8	0.9961	250
TR - T - ΔP	k ≥ 150	σ = 0.4591 + 0.026 (A) + 0.5313 (B) + 0.004 (A)(B) - 0.2293 (C) - 1.3537 (D)	V.5.9	0.9903	375
Transverse cracking condition with negative temperature differential for slab without concrete shoulder			**Slab size: 2.0 m × 2.0 m**		
SA - T - ΔN	k <100	σ = -0.333 + 0.0086 (A) + 1.1127 (B) + 0.0045 (A)(B) + 0.2464 (C) + 0.2468 (D)	V.6.1	0.9961	250
SA - T - ΔN	100 ≤ k < 150	σ = -0.4375 + 0.0145 (A) + 1.0569 (B) + 0.0063 (A)(B) + 0.3061 (C) + 0.3592 (D)	V.6.2	0.9934	250
SA - T - ΔN	k ≥ 150	σ = -0.6363 + 0.0246 (A) + 0.9773 (B) + 0.0081 (A)(B) + 0.407 (C) + 0.5048 (D)	V.6.3	0.9835	375
TA - T - ΔN	k <100	σ = -0.7313 + 0.0103 (A) + 0.5657 (B) + 0.001 (A)(B) + 0.3936 (C) - 0.474 (D)	V.6.4	0.9973	250
TA - T - ΔN	100 ≤ k < 150	σ = -0.9234 + 0.0149 (A) + 0.5614 (B) + 0.0025 (A)(B) + 0.4427 (C) - 0.5715 (D)	V.6.5	0.9968	250
TA - T - ΔN	k ≥ 150	σ = -1.2051 + 0.0253 (A) + 0.5567 (B) + 0.0031 (A)(B) + 0.5158 (C) - 0.6445 (D)	V.6.6	0.9928	375
TR - T - ΔN	k <100	σ = -0.7313 + 0.0103 (A) + 0.3771 (B) + 0.0007 (A)(B) + 0.3936 (C) - 0.474 (D)	V.6.7	0.9973	250
TR - T - ΔN	100 ≤ k < 150	σ = -0.9234 + 0.0149 (A) + 0.3743 (B) + 0.0017 (A)(B) + 0.4427 (C) - 0.5715 (D)	V.6.8	0.9968	250
TR - T - ΔN	k ≥ 150	σ = -1.2051 + 0.0253 (A) + 0.3711 (B) + 0.0021 (A)(B) + 0.5158 (C) - 0.6445 (D)	V.6.9	0.9928	375

SA = Single Axle; TA= Tandem Axle; TR= Tridem Axle; T = Transverse cracking; L= Longitudinal cracking; ΔP= Positive temperature differential; ΔN= Negative temperature differential; A= ΔT; B= Ph/kl⁴ ; C= $\log_{10}(k)$; D= $\log_{10}(l)$; k= Effective Modulus of subgrade reaction, MPa/m

Appendix-B

Illustrative Example of Thickness Design of SSCP

The design example presented here is taken from the IRC:58 design example, where the design thickness for pavements with tied concrete shoulder case is 290 mm and for pavement without tied concrete shoulder case, the design thickness is 330 mm.

Design Example

A cement concrete pavement is to be designed for a four-lane divided National Highway with two lanes in each direction in the state of Bihar. Design the pavement for a period of 30 years. It is expected that the road will carry, in the year of completion of construction, about 3000 commercial vehicles per day in each direction. Axle load survey of commercial vehicles indicated that the percentages of front single (steering) axle, rear single axle, rear tandem axle and rear tridem axle are 45%, 15%, 25% and 15% respectively. Traffic count indicates that 60% of the commercial vehicles travel during night hours (6 PM to 6 AM).

Details of axle load spectrum of rear single, tandem and tridem axles are given in **Table B-1.** Front (steering) axles are not included. The average number of axles per commercial vehicle is 2.35 (due to the presence of multi-axle vehicles).

Table B-1 Axle Load Spectrum for the Example

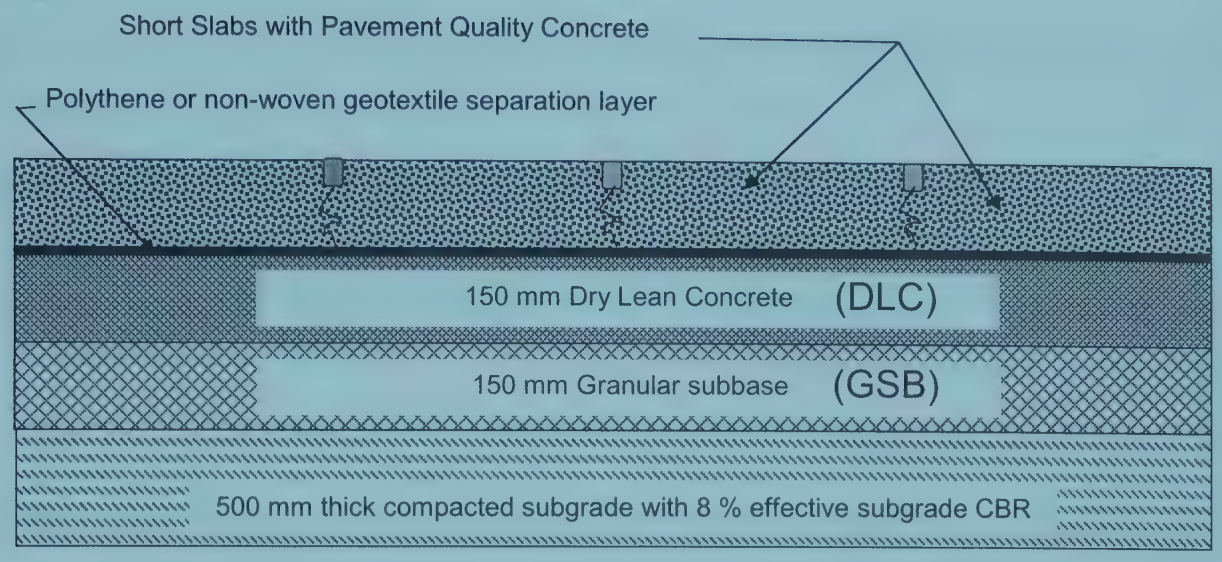
Single Axle		Tandem Axle		Tridem Axle	
Axle Load Class kN	Frequency (% of Single Axles)	Axle Load Class kN	Frequency (% of Tandem Axles)	Axle Load Class kN	Frequency (% of Tridem Axles)
185-195	18.15	380-400	14.5	530-560	5.23
175-185	17.43	360-380	10.5	500-530	4.85
165-175	18.27	340-360	3.63	470-500	3.44
155-165	12.98	320-340	2.50	440-470	7.12
145-155	2.98	300-320	2.69	410-440	10.11
135-145	1.62	280-300	1.26	380-410	12.01
125-135	2.62	260-280	3.90	350-380	15.57
115-125	2.65	240-260	5.19	320-350	13.28
105-115	2.65	220-240	6.30	290-320	4.55
95-105	3.25	200-220	6.40	260-290	3.16
85-95	3.25	180-200	8.90	230-260	3.1
< 85	14.15	< 180	34.23	< 230	17.58
	100		100		100

Effective CBR of compacted subgrade = 8 %.

Design a concrete pavement with different slab sizes for concrete pavement with concrete shoulder case and for concrete pavement without shoulder case.

Solution for the Example

For the purpose of this example, SSCP with tied shoulder section, as illustrated in the following figure, is proposed.


Short Slabs with Pavement Quality Concrete
Polythene or non-woven geotextile separation layer
150 mm Dry Lean Concrete (DLC)
150 mm Granular subbase (GSB)
500 mm thick compacted subgrade with 8 % effective subgrade CBR

Selection of modulus of subgrade reaction (k)

- Effective CBR of compacted subgrade = 8%.
- Modulus of subgrade reaction = 50.3 MPa/m (from Table 2 of IRC:58)
- Provide 150 mm thick granular subbase
- Provide a DLC layer of 150 mm thickness with DLC having a minimum 7-day compressive strength of 7 MPa
- Effective modulus of subgrade reaction of combined foundation of subgrade + granular subbase and DLC subbase (from Table 4 of IRC:58 by interpolation) = 285 MPa/m

Provide a de-bonding layer of polythene sheet of 125 microns thickness between the DLC layer and the concrete slab.

Selection of Flexural Strength of Concrete

- 28-day Compressive strength of cement concrete ≥ 40 MPa minimum
- 90-day Compressive strength of cement concrete ≥ 48 MPa
- 28-day Flexural strength of cement concrete = 4.5 MPa (minimum)
- 90-day Flexural strength of cement concrete = 4.5 × 1.1 = 4.95 MPa

Selection of Design Traffic for Fatigue Analysis

- Design period = 30 years
- Annual rate of growth of commercial traffic (expressed in decimal) = 0.075 (assumed)
- Two-way commercial traffic volume per day = 6000 commercial vehicles/day
- % of traffic in predominant direction = 50 % (3000 CVs in each direction)
- Total two-way commercial vehicles during design period, C is estimated as

$$C = \frac{365 \times 6000 \times [(1 + 0.075)^{30} - 1]}{0.075}$$

$$= \quad 226{,}444{,}692 \text{ CVs}$$

- Average number of axles (steering/ single/ tandem/ tridem) per commercial vehicle = 2.35
- Total two-way axle load repetitions during the design period = 22,64,44,692 x 2.35 = 53,21,45,025 axles
- Number of axles in predominant direction = 53,21,45,025 x 0.5 = 26,60,72,513

Note:

In IRC:58, tandem axle repetitions were taken only once and tridem axle repetitions were totally ignored for BUC case in the transverse cracking analysis. In the design of SSCP, the number of repetitions is doubled for tandem and tridem as the same critical load positions occur twice in the case of tandem and tridem axles for BUC in transverse cracking.

For Transverse Cracking Analysis

- Wheel wander factor for Transverse cracking with positive temperature differential and wheel placement near longitudinal edge = 0.25
- Wheel wander factor for Transverse cracking with negative temperature differential (wheel placement near the longitudinal edge) = 0.25
- Lateral Placement factor for day time (for multilane highways) = 0.125
- Lateral Placement factor for night time (for multilane highways) = 0.125
- Factor for selection of traffic for BUC analysis (for 6-hour period during day) = 50% of 0.4 (which is for 12 hour) = 0.2
- Factor for selection of traffic for TDC analysis (for 6-hour period during day) = 50% of 0.6 (which is for 12 hour) = 0.3
- Design axle repetitions for BUC analysis (for 6-hour day time traffic) = 133,03,626
- Design axle repetitions for TDC analysis (for 6-hour night time traffic) = 199,55,438
- Category-wise axle load repetitions for bottom-up and top-down fatigue cracking analysis are given in **Table B-2**.

Table B-2 Estimated Axle Repetitions for BUC and TDC Transverse Cracking Analysis

Axle category	Proportion of the Axle-Category	Category-wise axle repetitions for	
		Bottom- up Cracking analysis	Top-Down Cracking analysis
Front (steering) single	0.45	59,86,632 (133,03,626 * 0.45)	89,79,947 (199,55,438 * 0.45)
Rear single	0.15	19,95,544 (13303626 * 0.15)	29,93,316 (199,55,438 * 0.15)
Rear Tandem	0.25	66,51,813 # (133,03,626 * 0.25 * 2)	49,88,860 (199,55,438 * 0.25)
Rear Tridem	0.15	39,91,088 # (133,03,626 * 0.15 * 2)	29,93,316 (199,55,438 * 0.15)

*(**Note:** For tandem and tridem axles, number of repetitions is multiplied by a factor of 2 for bottom-up transverse cracking case only)*

For Longitudinal Cracking Analysis

- Wheel wander factor for Longitudinal cracking positive temperature differential (wheel placement near longitudinal edge) = 0.25
- Wheel wander factor for Transverse cracking with negative temperature differential (wheel placement near longitudinal edge) = 0.25
- Lateral Placement factor for day time (for multilane highways) = 0.125
- Factor for selection of traffic for BUC analysis (for 6-hour period during day) = 0.20
- Factor for selection of traffic for TDC analysis (for 6-hour period during day) = 0.30
- Design axle repetitions for BUC analysis (for 6-hour day time traffic) = 133,03,626
- Lateral Placement factor for night time (for multilane highways) = 0.125
- Design axle repetitions for TDC analysis (for 6-hour night time traffic) =199,55,438
- The corresponding axle category-wise distribution for BUC and TDC analysis is presented in **Table B-3**.

Table B-3 Estimated Axle Repetitions for BUC and TDC Longitudinal Cracking Analysis

Axle category	Proportion of the Axle-Category	Category-wise axle repetitions for	
		Bottom- up Cracking analysis	Top- Down Cracking analysis
Front (steering) single	0.45	59,86,632 (133,03,626 * 0.45)	89,79,947 (199,55,438 * 0.45)
Rear single	0.15	19,95,544 (133,03,626 * 0.15)	29,93,316 (199,55,438 * 0.15)
Rear Tandem	0.25	33,25,906 (13303626 * 0.25)	49,88,860 (199,55,438 * 0.25)
Rear Tridem	0.15	19,95,544 (133,03,626 * 0.15)	29,93,316 (199,55,438 * 0.15)

Cumulative Fatigue Damage Analysis

Cumulative Fatigue Damage (CFD) analysis for Bottom-Up Cracking (BUC) and Top-Down Cracking (TDC) and selection of slab thickness:

- Effective modulus of subgrade reaction of foundation, k = 285 MPa/m
- Elastic Modulus of concrete, E = 30,000 MPa
- Poisson's ratio of concrete, μ = 0.15
- Unit weight of concrete, γ = 24 kN/m^3
- Design flexural strength of concrete = 4.95 MPa

- Max. day-time Temperature Differential in slab (for bottom-up cracking) = 16.6°C (for Bihar) [the same value of temperature differential of 16.6°C has been considered for all the slab thicknesses for the purpose of illustration. The actual temperature differential varies with slab thickness as indicated in Table 1 of IRC:58 guidelines]
- Night-time Temperature Differential in slab (for top-down cracking) = (Day-time diff/2) + 5 = 13.3°C

Trial Design: For slab size of 1.0 m x 1.0 m

- Select a trial thickness of 210 mm of short slab concrete layer
- Radius of relative stiffness, $l = [Eh^3/(12k(1-\mu^2))]^{0.25} = 0.537$ m
- Computation of bottom-up and top-down cumulative fatigue damage for transverse cracking analysis is illustrated in **Tables B-4 and B-5** for transverse cracking case for 210 mm thickness. The analysis for longitudinal bottom-up and top-down cracking is presented in **Tables B-6 and B-7** for the slab thickness of 210 mm.
- The sum of the cumulative fatigue damage values estimated for bottom-up and top-down cracking for transverse cracking case is 0.764 which is less than 1.0. Hence, the design is OK for transverse cracking.
- The sum of the cumulative fatigue damage values estimated for bottom-up and top-down cracking for longitudinal cracking case is 0.0 which is less than 1.0. Hence, the design is OK for longitudinal cracking.
- **Table B-8** presents the summary of the cumulative fatigue damage carried out with different slab thicknesses for comparison of 1.0 m x 1.0 m slab size
- **Table B-9** presents the summary of the Cumulative Fatigue Damage (CFD) estimated for the SSCP with and without concrete shoulder for different slab sizes and thicknesses for the purpose of comparison of the design slab thicknesses obtained with different slab sizes.

Table B-4 Cumulative Fatigue Damage Analysis for BUC for Transverse Cracking for with Concrete Shoulder Case (1.0 m × 1.0 m)

(Axle loads are not shown in the table. The mid-point axle load values of different axle load groups mentioned in Table B-1 were used for calculation of tensile stress. For example, the 3,62,191 axle repetitions mentioned in column-1 correspond to 185 to 195 kN single axle group)

Bottom-up Cracking (BUC) Fatigue Analysis for Day-time (6 hour) traffic and Positive Temperature Differential														
Rear Single Axles					Rear Tandem Axles					Rear Tridem Axles				
Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)	Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)	Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)
3,62,191	2.346	0.474	37,57,699	0.096	9,64,513	2.407	0.486	15,97,822	0.604	2,08,734	2.244	0.453	3,55,24,943	0.0059
3,47,823	2.223	0.449	infinite	0	6,98,440	2.285	0.462	1,19,78,689	0.058	1,93,568	2.121	0.429	infinite	0
3,64,586	2.101	0.424	infinite	0	2,41,461	2.162	0.437	infinite	0	1,37,293	1.999	0.404	infinite	0
2,59,022	1.978	0.400	infinite	0	1,66,295	2.040	0.412	infinite	0	2,84,165	1.876	0.379	infinite	0
59,467	1.855	0.375	infinite	0	1,78,934	1.917	0.387	infinite	0	4,03,499	1.754	0.354	infinite	0
32,328	1.732	0.350	infinite	0	83,813	1.794	0.363	infinite	0	4,79,330	1.631	0.330	infinite	0
52,283	1.610	0.325	infinite	0	2,59,421	1.672	0.338	infinite	0	6,21,412	1.508	0.305	infinite	0
52,882	1.487	0.300	infinite	0	3,45,229	1.549	0.313	infinite	0	5,30,016	1.386	0.280	infinite	0
52,882	1.364	0.276	infinite	0	4,19,064	1.427	0.288	infinite	0	1,81,594	1.263	0.255	infinite	0
64,855	1.242	0.251	infinite	0	4,25,716	1.304	0.263	infinite	0	1,26,118	1.141	0.230	infinite	0
64,855	1.119	0.226	infinite	0	5,92,011	1.182	0.239	infinite	0	1,23,724	1.018	0.206	infinite	0
2,82,369	0.996	0.201	infinite	0	22,76,916	1.059	0.214	infinite	0	7,01,633	0.896	0.181	infinite	0
19,95,544	Fat Dam from Single Axles =			0.0964	66,51,813	Fat Dam from Tandem Axles =			0.662	39,91,088	Fat Dam from Tridem Axles =			0.0059
Total Bottom-up Fatigue Damage due to single, tandem and tridem axle loads =					0.0964			+		0.6619	+	0.0059	=	0.764

Table B-5 Cumulative Fatigue Damage Analysis for TDC for Transverse Cracking for with Concrete Shoulder Case (1.0 m × 1.0 m)

(Axle loads are not shown in the table. The mid-point axle load values of different axle load groups mentioned in Table B-1 were used for calculation of tensile stress. For example, the 5,43,287 axle repetitions mentioned in column-1 correspond to 185 to 195 kN single axle group)

Top-Down Cracking (TDC) Fatigue Analysis for Night-time (6 hour) traffic and Negative Temperature Differential														
Rear Single Axles					Rear Tandem Axles					Rear Tridem Axles				
Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)	Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)	Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)
5,43,287	1.220	0.247	infinite	0	7,23,385	1.468	0.297	infinite	0	1,56,550	1.376	0.278	infinite	0
5,21,735	1.158	0.234	infinite	0	5,23,830	1.399	0.283	infinite	0	1,45,176	1.307	0.264	infinite	0
5,46,879	1.096	0.221	infinite	0	1,81,096	1.330	0.269	infinite	0	1,02,970	1.238	0.250	infinite	0
3,88,532	1.034	0.209	infinite	0	1,24,721	1.261	0.255	infinite	0	2,13,124	1.168	0.236	infinite	0
89,201	0.972	0.196	infinite	0	1,34,200	1.191	0.241	infinite	0	3,02,624	1.099	0.222	infinite	0
48,492	0.911	0.184	infinite	0	62,860	1.122	0.227	infinite	0	3,59,497	1.030	0.208	infinite	0
78,425	0.849	0.171	infinite	0	1,94,566	1.053	0.213	infinite	0	4,66,059	0.961	0.194	infinite	0
79,323	0.787	0.159	infinite	0	2,58,922	0.984	0.199	infinite	0	3,97,512	0.892	0.180	infinite	0
79,323	0.725	0.146	infinite	0	3,14,298	0.915	0.185	infinite	0	1,36,196	0.823	0.166	infinite	0
97,283	0.663	0.134	infinite	0	3,19,287	0.846	0.171	infinite	0	94,589	0.754	0.152	infinite	0
97,283	0.601	0.121	infinite	0	4,44,009	0.777	0.157	infinite	0	92,793	0.685	0.138	infinite	0
4,23,554	0.539	0.109	infinite	0	17,07,687	0.708	0.143	infinite	0	5,26,225	0.616	0.124	infinite	0
29,93,316	Fat Dam from Single Axles =			0	49,88,860	Fat Dam from Tandem Axles =			0	29,93,316	Fat Dam from Tridem Axles =			0
Total Top-Down Fatigue Damage due to single, tandem and tridem axle loads=								0	+	0	+	0	=	0

Table B-6 Cumulative Fatigue Damage Analysis for BUC for Longitudinal Cracking for with Concrete Shoulder Case (1.0 m × 1.0 m)

(Axle loads are not shown in the table. The mid-point axle load values of different axle load groups mentioned in Table B-1 were used for calculation of tensile stress. For example, the 3,62,191 axle repetitions mentioned in column-1 correspond to 185 to 195 kN single axle group)

Bottom-up Cracking (BUC) Fatigue Analysis for Day-time (6 hour) traffic and Positive Temperature Differential														
Rear Single Axles					Rear Tandem Axles					Rear Tridem Axles				
Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)	Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)	Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)
3,62,191	1.555	0.314	infinite	0	4,82,256	1.605	0.324	infinite	0	1,04,367	1.495	0.302	infinite	0
3,47,823	1.473	0.298	infinite	0	3,49,220	1.522	0.308	infinite	0	96,784	1.412	0.285	infinite	0
3,64,586	1.391	0.281	infinite	0	1,20,730	1.440	0.291	infinite	0	68,647	1.330	0.269	infinite	0
2,59,022	1.309	0.264	infinite	0	83,148	1.357	0.274	infinite	0	1,42,083	1.248	0.252	infinite	0
59,467	1.227	0.248	infinite	0	89,467	1.275	0.258	infinite	0	2,01,749	1.165	0.235	infinite	0
32,328	1.145	0.231	infinite	0	41,906	1.193	0.241	infinite	0	2,39,665	1.083	0.219	infinite	0
52,283	1.063	0.215	infinite	0	1,29,710	1.110	0.224	infinite	0	3,10,706	1.000	0.202	infinite	0
52,882	0.981	0.198	infinite	0	1,72,615	1.028	0.208	infinite	0	2,65,008	0.918	0.185	infinite	0
52,882	0.899	0.182	infinite	0	2,09,532	0.945	0.191	infinite	0	90,797	0.836	0.169	infinite	0
64,855	0.818	0.165	infinite	0	2,12,858	0.863	0.174	infinite	0	63,059	0.753	0.152	infinite	0
64,855	0.736	0.149	infinite	0	2,96,006	0.781	0.158	infinite	0	61,862	0.671	0.136	infinite	0
2,82,369	0.654	0.132	infinite	0	11,38,458	0.698	0.141	infinite	0	3,50,817	0.588	0.119	infinite	0
19,95,544	Fat Dam from Single Axles =			0	33,25,906	Fat Dam from Tandem Axles =			0	19,95,544	Fat Dam from Tridem Axles =			0
Total Bottom-up Fatigue Damage due to single, tandem and tridem axle loads =								0	+	0	+	0	=	0

Table B-7 Cumulative Fatigue Damage Analysis for TDC for Longitudinal Cracking for with Concrete Shoulder Case (1.0 m × 1.0 m)

(Axle loads are not shown in the table. The mid-point axle load values of different axle load groups mentioned in Table B-1 were used for calculation of tensile stress. For example, the 5,43,287 axle repetitions mentioned in column-1 correspond to 185 to 195 kN single axle group)

Top-Down Cracking (TDC) Fatigue Analysis for Night-time (6 hour) traffic and Negative Temperature Differential														
Rear Single Axles					Rear Tandem Axles					Rear Tridem Axles				
Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)	Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)	Expected Repetitions (ni)	Flex Stress MPa	Stress Ratio (SR)	Allowable Repetitions (Ni)	Fatigue Damage (ni/Ni)
5,43,287	1.419	0.287	infinite	0	7,23,385	1.433	0.290	infinite	0	1,56,550	1.347	0.272	infinite	0
5,21,735	1.351	0.273	infinite	0	5,23,830	1.367	0.276	infinite	0	1,45,176	1.280	0.259	infinite	0
5,46,879	1.283	0.259	infinite	0	1,81,096	1.300	0.263	infinite	0	1,02,970	1.213	0.245	infinite	0
3,88,532	1.215	0.245	infinite	0	1,24,721	1.234	0.249	infinite	0	2,13,124	1.147	0.232	infinite	0
89,201	1.147	0.232	infinite	0	1,34,200	1.167	0.236	infinite	0	3,02,624	1.080	0.218	infinite	0
48,492	1.079	0.218	infinite	0	62,860	1.101	0.222	infinite	0	3,59,497	1.014	0.205	infinite	0
78,425	1.011	0.204	infinite	0	1,94,566	1.034	0.209	infinite	0	4,66,059	0.947	0.191	infinite	0
79,323	0.943	0.191	infinite	0	2,58,922	0.968	0.195	infinite	0	3,97,512	0.880	0.178	infinite	0
79,323	0.875	0.177	infinite	0	3,14,298	0.901	0.182	infinite	0	1,36,196	0.814	0.164	infinite	0
97,283	0.807	0.163	infinite	0	3,19,287	0.834	0.169	infinite	0	94,589	0.747	0.151	infinite	0
97,283	0.739	0.149	infinite	0	4,44,009	0.768	0.155	infinite	0	92,793	0.680	0.137	infinite	0
4,23,554	0.671	0.136	infinite	0	17,07,687	0.701	0.142	infinite	0	5,26,225	0.614	0.124	infinite	0
29,93,316	Fat Dam from Single Axles =			0	49,88,860	Fat Dam from Tandem Axles =			0	29,93,316	Fat Dam from Tridem Axles =			0
Total Top-Down Fatigue Damage due to single, tandem and tridem axle loads=							0	+	0	+	0	=		0

Table B-8 Cumulative Fatigue Damage values for different Slab Thicknesses for with Concrete Shoulder Case (1.0 m × 1.0 m)

Slab Thickness, (m)	CFD for BUC Case				CFD for TDC Case				CFD (Sum of BUC &TDC)	Remarks
	Due to Rear Single Axles	Due to Tandem Axles	Due to Tridem Axles	Total CFD	Due to Rear Single Axles	Due to Tandem Axles	Due to Rear Tridem Axles	Total CFD		
Transverse Cracking										
0.18	77.26	280.68	20.35	378.28	0	0	0	0	378.28	Unsafe
0.19	11.83	40.91	3.10	55.84	0	0	0	0	55.84	Unsafe
0.20	1.78	7.14	0.35	9.27	0	0	0	0	9.27	Unsafe
0.21	0.10	0.66	0.01	0.76	0	0	0	0	0.76	Safe
Longitudinal Cracking										
0.18	0	0.01	0	0.01	0	0	0	0	0.01	Safe
0.19	0	0	0	0	0	0	0	0	0	Safe
0.20	0	0	0	0	0	0	0	0	0	Safe
0.21	0	0	0	0	0	0	0	0	0	Safe

Table B-9 Cumulative Fatigue Damage Values for different Slab Sizes for with and without Concrete Shoulder Cases

Slab Thickness, (m)	CFD for BUC Case				CFD for TDC Case				CFD (Sum of BUC & TDC)	Remarks
	Due to Rear Single Axles	Due to Tandem Axles	Due to Tridem Axles	Total CFD	Due to Rear Single Axles	Due to Tandem Axles	Due to Rear Tridem Axles	Total CFD		
1.0 m x 1.0 m slab without concrete shoulder										
Transverse Cracking										
0.20	6.574	19.364	1.326	27.264	0	0	0	0	27.264	Unsafe
0.21	0.799	2.871	0.085	3.754	0	0	0	0	3.754	Unsafe
0.215	0.176	0.755	0.007	0.939	0	0	0	0	0.939	Safe
Longitudinal Cracking										
0.20	0	0	0	0	0	0	0	0	0	Safe
0.21	0	0	0	0	0	0	0	0	0	Safe
0.215	0	0	0	0	0	0	0	0	0	Safe
1.25 m x 1.25 m with concrete shoulder										
Transverse Cracking										
0.20	24.30	40.746	3.216	68.263	0	1.426	0.035	1.462	69.726	Unsafe
0.21	4.984	8.510	0.483	13.978	0	0.0769	0	0.0769	14.054	Unsafe
0.22	0.773	1.183	0.021	1.978	0	0	0	0	1.978	Unsafe
0.225	0.218	0.280	0	0.498	0	0	0	0	0.498	Safe
Longitudinal Cracking										
0.20	0.0097	0.131	0	0.141	0	0	0	0	0.1410	Safe

0.21	0	0	0	0	0	0	0	0	0	Safe
0.22	0	0	0	0	0	0	0	0	0	Safe
0.225	0	0	0	0	0	0	0	0	0	Safe
1.25 m x 1.25 m without concrete shoulder										
Transverse Cracking										
0.21	13.224	18.920	1.339	33.485	0	0.140	0	0.140	33.625	Unsafe
0.22	2.448	3.358	0.116	5.922	0	0	0	0	5.922	Unsafe
0.225	0.871	1.053	0.015	1.940	0	0	0	0	1.940	Unsafe
0.23	0.235	0.209	0	0.445	0	0	0	0	0.445	Safe
Longitudinal Cracking										
0.21	0	0	0	0	0	0	0	0	0	Safe
0.22	0	0	0	0	0	0	0	0	0	Safe
0.225	0	0	0	0	0	0	0	0	0	Safe
0.23	0	0	0	0	0	0	0	0	0	Safe
1.5 m x 1.5 m with concrete shoulder										
Transverse Cracking										
0.22	9.885	12.419	0.945	23.251	0	19.674	1.708	21.383	44.634	Unsafe
0.24	0.413	0.304	0	0.718	0	3.750	0.224	3.975	4.693	Unsafe
0.25	0.025	0	0	0.0250	0	1.520	0.065	1.586	1.611	Unsafe
0.255	0	0	0	0	0	0.931	0.032	0.963	0.963	Safe
Longitudinal Cracking										
0.22	0	1.035	0.040	1.075	0	0	0	0	1.075	Unsafe
0.24	0	0	0	0	0	0	0	0	0	Safe

0.25	0	0	0	0	0	0	0	0	0	Safe
0.255	0	0	0	0	0	0	0	0	0	Safe
1.5 m x 1.5 m without concrete shoulder										
Transverse Cracking										
0.22	20.846	22.848	1.905	45.60	0	16.683	1.483	18.166	63.767	Unsafe
0.24	0.864	0.671	0.009	1.545	0	1.970	0.096	2.067	3.612	Unsafe
0.25	0.058	0	0	0.058	0	0.483	0.011	0.494	0.552	Safe
Longitudinal Cracking										
0.22	0	1.035	0.040	1.07581	0	0	0	0	1.075	Unsafe
0.24	0	0	0	0	0	0	0	0	0	Safe
0.25	0	0	0	0	0	0	0	0	0	Safe
1.75 m x 1.75 m with concrete shoulder										
Transverse Cracking										
0.24	3.859	3.788	0.320	7.968	0	0	0	0	7.968	Unsafe
0.25	0.811	0.563	0.023	1.398	0	0	0	0	1.398	Unsafe
0.255	0.296	0.135	0	0.431	0	0	0	0	0.431	Safe
Longitudinal Cracking										
0.24	0	0.651	0.019	0.670	0	0.098	0	0.098	0.769	Safe
0.25	0	0.072	0	0.072	0	0	0	0	0.072	Safe
0.255	0	0.015	0	0.015	0	0	0	0	0.015	Safe
1.75 m x 1.75 m without concrete shoulder										
Transverse Cracking										
0.24	7.253	6.940	0.651	14.846	0	0	0	0	14.846	Unsafe
0.25	1.60	1.219	0.063	2.882	0	0	0	0	2.882	Unsafe
0.255	0.618	0.360	0.009	0.989	0	0	0	0	0.989	Safe

Longitudinal Cracking										
0.24	0	0.651	0.019	0.670	0	0.098	0	0.098	0.769	Safe
0.25	0	0.072	0	0.072	0	0	0	0	0.072	Safe
0.255	0	0.015	0	0.015	0	0	0	0	0.015	Safe
2.0 m x 2.0 m with concrete shoulder										
Transverse Cracking										
0.25	11.612	10.616	1.190	23.419	0	0	0	0	23.419	Unsafe
0.26	4.140	3.293	0.274	7.708	0	0	0	0	7.708	Unsafe
0.27	1.256	0.701	0.031	1.989	0	0	0	0	1.989	Unsafe
0.275	0.617	0.252	0.007	0.877	0	0	0	0	0.877	Safe
Longitudinal Cracking										
0.25	0.271	2.783	0.202	3.256	0.010	3.464	0.244	3.719	6.976	Unsafe
0.26	0.024	0.899	0.041	0.965	0	1.502	0.078	1.580	2.546	Unsafe
0.27	0	0.212	0.004	0.216	0	0.593	0.018	0.611	0.828	Safe
0.275	0	0.084	0	0.084	0	0.353	0.008	0.362	0.446	Safe
2.0 m x 2.0 m without concrete shoulder										
Transverse Cracking										
0.25	18.515	15.181	1.737	35.434	0	0	0	0	35.434	Unsafe
0.27	1.674	0.970	0.046	2.691	0	0	0	0	2.691	Unsafe
0.28	0.310	0.081	0	0.392	0	0	0	0	0.392	Safe
Longitudinal Cracking										
0.25	0.271	2.783	0.202	3.256	0.010	3.464	0.244	3.719	6.976	Unsafe
0.27	0	0.212	0.004	0.216	0	0.593	0.018	0.611	0.828	Unsafe
0.28	0	0.025	0	0.025	0	0.203	0.003	0.207	0.233	Safe

Appendix C

Some Details about the SSCP Test Sections Constructed on NH-18

C.1 General Details of the Test Sections

Two separate SSCP sections, each of 1.5 km length, were constructed on National Highway NH18 over (i) a newly constructed Dry Lean Concrete (DLC) subbase and (ii) existing bituminous pavement. The details of the test sections are presented in the following section. Some observation made on the basis of structural evaluation carried out seasonally and about the functional condition of the test sections are also included in this appendix.

IIT Kharagpur and NHAI, New Delhi jointly identified two stretches of NH-18 for construction of SSCP test sections. Both these stretches were part of four-laning work of Mahulia- Baharagora – JH/WB- Border section of NH18 in the state of Jharkhand under NHDP- III. The existing two-lane road was rehabilitated as a concrete pavement on the Right-Hand Side (RHS) and the Left-Hand Side (LHS) carriageway was upgraded with new two-lane Jointed Plain Concrete Pavement (JPCP). As per the Detailed Project Report (DPR) of the work, the 20-year (7054 CVPD) pavement design adopted was 280 mm thick PQC over a foundation of 150 mm thick DLC and 150 mm thick GSB layer with an effective subgrade CBR value of 9 %.

Two SSCP test sections of 1.5 km length each, were constructed by the Contractor in the RHS carriageway at the following chainages during July 2017 and January 2018.

SSCP over Existing Bituminous Pavement

(a) km. 54+000 to km. 54+900 (900 m) near Baharagora and

(b) km. 3+320 to 3+620 and km 5+990 to km. 6+290 (600 m) in Ghatshila town in Jharkhand state.

Details of different combinations of panel size, slab thickness and use of sealant tried in these stretches are given in **Tables C-1 and C-2** respectively for the above two test stretches.

Table C-1 Details of SSCP Test Section on DBM Stretch near Baharaghora

Panel Size (m×m)	Thickness (mm) - PQC	Sealant	Chainage (km)	Length (m)	Remarks
1.0 × 1.0	180	Yes	54+000 to 54+200	200	0.9 kg/cum fibre*
1.0 × 1.0	180	Yes	54+200 to 54+250	50	without fibre
1.0 × 1.0	180	Yes	54+250 to 54+300	50	1.8 kg/cum fibre*
1.0 × 1.0	200	Yes	54+300 to 54+400	100	0.9 kg/cum fibre*
1.0 × 1.0	220	Yes	54+800 to 54+900	100	
1.5 × 1.5	200	Yes	54+400 to 54+600	200	
1.5 × 1.5	220	Yes	54+600 to 54+800	200	

**micro fibres were used to minimize the shrinkage cracking due to the larger surface area to volume ratio*

Table C-2 Details of SSCP Test Section on DBM Stretch near Ghatshila

Panel Size (m × m)	Thickness (mm) of PQC	Sealant	Chainage(km)	Length (m)
1.0 × 1.0	180	No	5+990 to 6+040	50
1.0 × 1.0	180	Yes	6+040 to 6+090	50
1.0 × 1.0	180	No	6+090 to 6+140	50
1.0 × 1.0	180	Yes	6+140 to 6+190	50
1.5 × 1.5	200	No	6+190 to 6+240	50
1.5 × 1.5	200	Yes	6+240 to 6+290	50
2.0 × 2.0	220	Yes	3+320 to 3+396	76
2.0 × 2.0	220	Yes	3+396 to 3+469	74
2.0 × 2.0	220	Yes	3+469 to 3+545	76
1.5 × 1.5	220	Yes	3+ 545 to 3+ 620	75

**micro fibres were used at a constant rate of 0.9 kg/cum to minimize the shrinkage cracking due to the larger surface area to volume ratio*

As the carriageway width of new concrete pavement is 9.0 m which is more than the carriageway width of the existing bituminous pavement (7.0 m), the additional width of 2.0 m was constructed from the subgrade onwards. The layer thicknesses and materials in the widened portion were matched with the cross section of the existing pavement structure. To account for the strengthened /consolidated subgrade condition of the existing pavement, 2.0 % cement content by weight was added to the newly laid granular base layers. The existing bituminous pavement had BC and DBM (I and II) layers. For the widened portion, DBM -II mix was used for full thickness equal to that of the existing bituminous layer.

SSCP over a Newly Constructed Dry Lean Concrete (DLC)

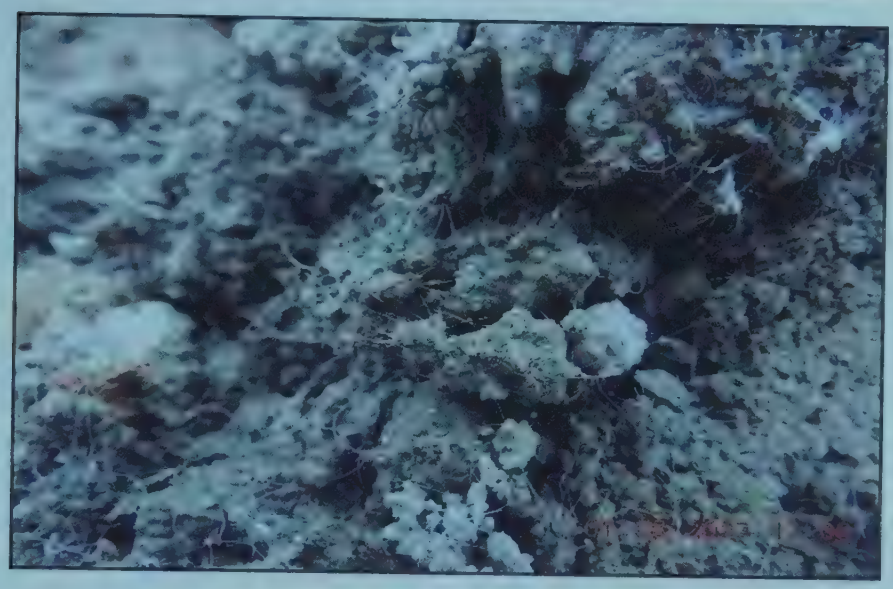
- km. 3+700 to km. 5+200 (1500 m) near Ghatshila town in Jharkhand state.

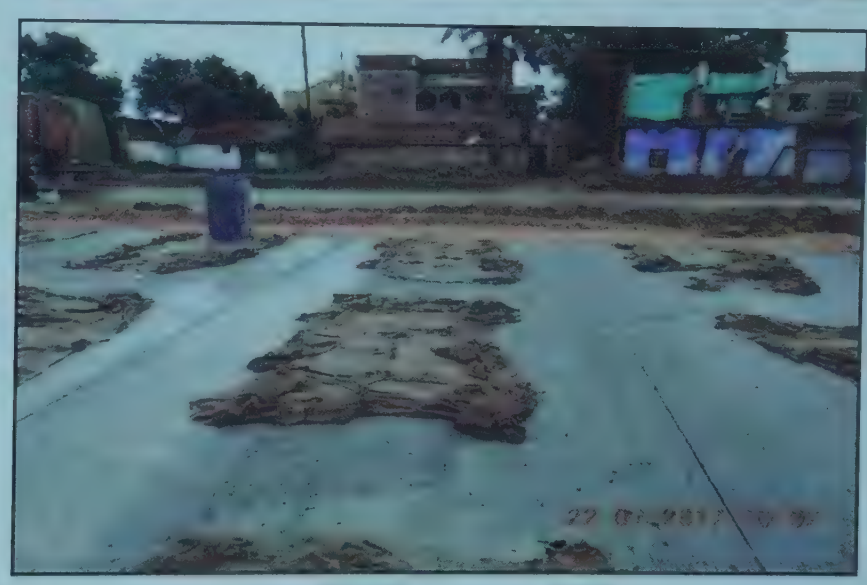
Details of different combinations of panel size, slab thickness and use of sealant tried in the above-mentioned stretch are given in **Table C-3**. Micro fibres were used at a constant rate of 0.9 kg/cum to minimize the shrinkage cracking due to the larger surface area to volume ratio.

Table C-3 Details of SSCP Test Section on DLC Stretch near Ghatshila

Panel Size (m x m)	Slab Thickness (mm)	Interface	Presence of Sealant	Chainage, km	Length (m)
1.0 x 1.0	180	Bonded	Yes	5+200 to 5+125	75
	180	Bonded	No	5+125 to 5+050	75
	180	Geotextile	No	5+050 to 4+975	75
	180	Geotextile	Yes	4+975 to 4+900	75
1.5 x 1.5	200	Geotextile	Yes	4+900 to 4+825	75
	200	Geotextile	No	4+825 to 4+750	75
	200	Bonded	No	4+750 to 4+675	75
	200	Bonded	Yes	4+675 to 4+600	75
	220	Bonded	Yes	4+600 to 4+550	50
	220	Geotextile	No	4+550 to 4+475	75
	220	Geotextile	Yes	4+475 to 4+450	25
1.0 x 1.0	220	Geotextile	No	4+450 to 4+375	75
	220	Geotextile	Yes	4+375 to 4+300	75
2.0 x 2.0	220	Geotextile	Yes	4+300 to 4+225	75
	220	Geotextile	No	4+225 to 4+150	75
	220	Bonded	No	4+150 to 4+075	75
	220	Bonded	Yes	4+075 to 4+000	75
1.0 x 1.0	220	Bonded	Yes	4+000 to 3+925	75
	220	Bonded	No	3+925 to 3+850	75
1.5 x 1.5	220	Bonded	No	3+850 to 3+775	75
	220	Bonded	Yes	3+775 to 3+750	25
	220	Geotextile	Yes	3+750 to 3+700	50

Fig. C-1 shows the photographs of different operations of construction of SSC slab over DBM layer. **Fig. C-2** shows the photographs of different operations of construction of SSC slab over DLC layer (Sridhar Reddy, 2023).





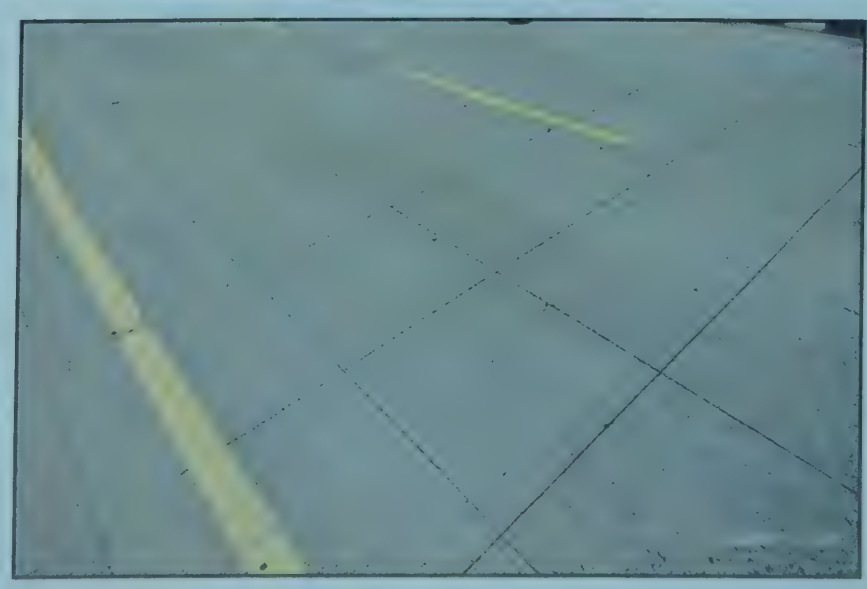


Fig. C-1 Different Operations of Construction of SSC Slab over DBM Layer

Fig. C-2 Different Operations of Construction of SSC Slab over DLC Layer

C-2 Some Observations on the Construction Methodology

The following observations are made from the construction of two test sections of SSCP on NH18.

- The construction of the 1500 m long NH-18 test section with two-lane carriageway with the paved shoulder was done in five days with a slip form paver and laser screed paver. Full width paving rather than a lane-by-lane construction is the ideal way of minimizing the number of construction joints and the use of dowel and tie bars. However, dowel bars should be used at construction joints.
- The two-level joint cutting system, adopted in the current project, was found to be effective to avoid random cracking. Joints were initially cut at an interval of 3.0 or 4.0 m depending on the slab size in both longitudinal and transverse directions. The second level groove cut was made at all the remaining joint locations.
- Both stages of cutting should be completed within a joint-cutting window of 8 to 16 hours.
- If the DLC layer is laid with a longitudinal joint, as was done in the current project, it is necessary to match this joint in DLC with that of SSCP. Mismatch of the DLC joint with that of SSCP, resulted in reflective longitudinal cracking at few locations in the PQC layer, especially when the PQC layer was bonded with DLC base. Use of a separation membrane (non-woven geotextile of 5 mm thick) between PQC and DLC base was found to be effective in preventing reflective cracks.
- The width of carriageway including paved shoulder is 9 m at test section in Ghatshila (km 3+320 to 5+200) and 9.5 m at test section in Baharagora (km 54+000 to 54+900). So, this necessitated a small change in the initial panel cutting pattern. 9 m width was initially cut into three panels of 3.0 m each across width. Similarly, 9.5 m width was initially cut into two panels of 3 m width and one panel of 3.5 m width.

C-3 Evaluation of Test Sections and Observations

The test sections were evaluated over a period of five years (2017-2022). Deflection Transfer Efficiency (DTE) of the joints was measured periodically using Falling Weight Deflectometer (FWD). A study was also carried on the effect of the joint crack width on DTE. The curling behavior of the SSCP slab was observed. International Roughness Index (IRI) measurement and distress mapping was done with the help of a network survey vehicle.

C-3-1 Structural Evaluation using Falling Weight Deflectometer

Falling Weight Deflectometer (FWD), which is an impulse-based equipment, is used for structural evaluation of pavement. Structural evaluation of SSCP test sections was done by applying a load of nearly 60 kN through a load plate of 300 mm diameter in different critical positions of the slab as shown in **Fig. C-3 (a) and (b)**. The response of the pavement (surface deflections at different distances) to the applied load was measured using a set of geophones placed at pre-defined spacing from the centre of load plate.

(a) **FWD Evaluation of SSCP at Joints**

(b) **Falling Weight Deflectometer (FWD) with Geophone for Measuring Surface Deflection of SSCP**

Fig. C-3 FWD Evaluation of SSC Pavement

The surface deflection data measured using the falling weight deflectometer was used to analyze the Deflection Transfer Efficiency (DTE) of joints. DTE is an important aspect in the concrete pavement performance as it defines the magnitude of wheel load transferred to the foundation as pressure and the resultant deflection which affects the possible erosion of the foundation. Joint crack width measurement was done periodically. Curling behavior of slabs was observed. The roughness of the surface of the pavement was measured using Bump Integrator and a Network Survey Vehicle (NSV).

Following are some of the observations from field evaluation of test sections of SSCP on NH-18 during the performance evaluation period of first five years as presented in NHAI Final report, 2022.

- FWD central deflection of 50-60 microns was observed for a typical load of 60 kN during the March and July months of 2018 for all the slab sizes and thicknesses adopted in the test sections, with an average value of $AREA_{36}$ parameter of 28.5 inch.
- The Deflection Transfer Efficiency (DTE) values for the joints of different slab sizes were in the range of 90 – 97.5% during May 2018 (Summer) and in the range of 78 – 93 % during January 2019 (Winter).
- The effect of joint spacing (slab size) and thickness of the slab on DTE was found to be minimal as the thicknesses of the test sections were in a narrow range (180 to 220 mm) and joint activation measures were not taken during the construction of test sections (Joga Rao, 2019). Suitable recommendation is made in these guidelines for effective joint activation.
- The temperature profile through the depth of the slab was found to be nearly bilinear during the day time in the month of May 2018 for the slabs of thickness 180, 200 and 220 mm.
- The observed crack widths were in the range of 0.2 to 0.5 mm where every second or third joint groove only developed into an active joint.
- A maximum curling magnitude of 350 microns was observed during May 2018 for a maximum positive temperature differential of 13.2°C for a slab of thickness 220 mm and the active joint spacing of 3 m.
- The shorter joint spacing did not have any adverse effect on the pavement roughness in terms of BI and IRI values obtained from the bump integrator testing and NSV data sets. There is no appreciable change in the IRI values between the SSCP and conventional CC pavements.

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